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RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND

TDIS-6001

CONTRACT AF [illegible]
PROJECT [illegible] TASK [illegible]

CADMIUM OXIDE

M. NEUBERGER

DATA SHEET DS-149

JUNE 1966

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PROJECT 7381; TASK 738103

6 # CADMIUM OXIDE,

9 Data sheets

10 M. NEUBERGER.

15 AF 33(615)-2460

16 AF-7381 17 738103

14 ~~DATA SHEET~~ DS-149

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12 53p.

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FOREWORD

This report was prepared by Hughes Aircraft Company, Culver City, California, under Contract Number AF 33(615)-2460, a continuation of work performed under Contract AF 33(615)-1235. The contract was initiated under Project No. 7381, "Materials Application," Task No. 738103, "Materials Information Development, Collection and Processing." The work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, with Mr. R. F. Klinger, Project Engineer.

The EPIC Information Analysis Center is a center for the collection, review and analysis of the scientific and technical literature on the electrical and electronic properties of materials. Its major function is to evaluate, compile and publish the experimental data from that literature. Through the medium of a series of publications such as Data Sheets, Special Reports, State-of-the-Art Reports, Computer Bibliographies, and services including special studies, answers to technical inquiries, research support is provided to the DoD community. EPIC input is primarily from the open literature. A large number of abstract journals, in addition to about 40 other journals, and the unclassified report literature are completely searched.

The initial step in the preparation of this data sheet was the retrieval, by means of a modified coordinate index, of all cadmium oxide literature in the EPIC file. Bibliographies were also reviewed to ensure the inclusion of all relevant literature. Those papers containing primary source data were selected unless only secondary references were available.

If equally valid data are available from several sources, all are given. Data are rejected when considered questionable because of faulty or dubious

measurements, unknown sample composition, or if more reliable and inclusive data are available from another source. Selection of data is based upon evaluation of that which is most representative, precise, reliable and inclusive over a wide range of parameters. The addition of new data to a material compilation requires a reappraisal of the reported values. Older data may be deleted in light of the new data.

Within every property section we have tried to include every available parameter and range of experimental condition in the literature. Information on test conditions and sample specification are extracted from the article. Some slight alterations in units and presentation may be made to facilitate comparison with other experimental data.

This report consists of the compiled data sheets on cadmium oxide. A full list of EPIC publications to date appears at the end of the report.

The author wishes to acknowledge the assistance afforded by Dr. J. J. Grossman in reviewing the experimental data, and the contribution of Mr. E. Schafer in the pre-publication review of the compilation. The supporting assistance of other members of the EPIC staff, in particular, Mrs. Jean Forest, Mr. Thomas Lyndon, and Mr. W. S. Hodge, is gratefully acknowledged.

ABSTRACT

These data sheets present a compilation of a wide range of electronic properties for cadmium oxide. Electrical properties include conductivity, dielectric constant, Hall coefficient, and mobility. Emission data have been broken down into the varied electron and photon emissions which result from application of electromagnetic energy over a wide spectrum. Energy data include energy bands, energy gap, and energy levels, as well as effective mass tables, and work function. The optical properties include absorption, reflection, and refractive index. Magnetic data are presented, as well as several other physical phenomena, such as Debye temperature. Thermoelectric and thermomagnetic properties are shown. Each property is compiled over the widest possible range of parameters including bulk and film form, from references obtained in a thorough literature search.

A summary of crystal structure and phase transitions has been included.

This report has been reviewed and is approved for publication.

Emil Schafer

Emil Schafer, Assistant Head
Electronic Properties Information Center

John W. Atwood

John W. Atwood
Project Manager

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INTRODUCTION

Cadmium oxide crystallizes in only one modification, the face-centered cubic (halite type). The crystals vary in color from black, brown or green to orange-yellow and yellow, depending on the amount of free cadmium present. Powders vary in color due to the particle size. The crystal growth plane is generally (110). The habit is cruciform, dendritic or arborescent, in addition to the acicular crystals which form in an arc-furnace.[1]

The lattice parameters have been measured numerous times. Bulk values range from $a_o = 4.6991$ Å to 4.690 Å for very pure material. For cadmium oxide "smoke", a value of 4.708 Å is given and for films two values; 4.69 Å and 4.71 Å.[1]

Donnay[2] gives two values for crystalline material; density is 8.15 g/cm^3 at 20°C.

$$a_o = 4.6943 \pm 0.0003 \text{ Å}$$
$$a_o = 4.708 \pm 0.002 \text{ Å}$$

Cadmium oxide decomposes in vacuum at 350°C and a metallic cadmium mirror appears. In air, sublimation begins at 900°C. The sublimation point, according to the latest available determination is 1564°C,[3] although lower values have been given.[1] The HANDBOOK OF CHEMISTRY AND PHYSICS[4] states that the sublimation point is above 1426°C.

Cadmium oxide and cadmium form solid solutions in all proportions. The dissociation constant of the cadmium oxide decreases strongly with increasing cadmium content. The saturated solution of cadmium in the oxide is almost non-dissociative. On the formation of the solid solution by heating in a vacuum, the lattice constant of the cubic oxide changes linearly with the excess cadmium. With the increase in a_o, the colour deepens until it becomes black. On heating, the interstitial cadmium sublimes. The presence of an excess of free electrons in the lattice of the solid solution is responsible for the n-type semiconductivity of cadmium oxide as well as its catalytic activity.[1]

The thermal conductivity decreases markedly with increase of oxygen pressure, indicating increases of interstitial oxygen in the cadmium oxide.[1]

Electrical and optical measurements on cadmium oxide were first made during the 1930's and 1940's when the use of cadmium oxide films for de-icing purposes was in the forefront. These films have a high resistivity with optical transmission in the visible green range of the spectrum. Other uses for the materials include storage batteries, as a catalyst with nickel oxide, as a toxic dust for pesticides and with phosphors in the preparation of electroluminescent devices. In this latter case, the cadmium oxide is employed as the conducting electrode or it is used to prepare a conducting transparent glass.[5]

Films of cadmium oxide are isotropic and have been grown epitaxially on cadmium surfaces.[6] These films are apparently unaffected by irradiation.[1] According to a very recent communication, pure cadmium oxide powder pellets show a 10 to 15% decrease in electrical resistivity after irradiation with 10^{14} to 10^{15} fast neutrons per sq. cm. (Ref. 24170) Adsorbed gases have a strong effect on both films and bulk surfaces, with respect to electrical conductivity and the change in the absorption edge. Cadmium oxide is known to give very strong surface activity as is evidenced by its use as a catalyst. (Ref. 11868)

According to Gmelin, cadmium oxide does not display any cathodoluminescence or fluorescence but does show photoconductivity.[7] The photoeffect is just extinguished at an incident illumination of .35 micron, a little below the visible.[1]

A method for growing single crystals by a vapor deposition technique is outlined in a paper by Fahrig.[8] The crystals are grown at 1125 to 1140°C and exhibit well-formed edges and faces in the (100) plane. They are black with a lattice constant of 4.6954 Å. Very low amounts of magnesium, silver and calcium impurities are present.

Cadmium oxide is not superconductive. (Ref. 13648)

Cadmium oxide films, when doped with copper and indium form a highly photovoltaic junction with selenium. Undoped films yield open circuit voltages up to 0.7 V in sunlight. Copper doping reduces the open circuit potential and indium doping increases

it. (Ref. 20405) Every film deposited at low temperatures is unstable. It must be stabilized by annealing. Time, temperature of preparation, stoichiometry, etc., must be determined experimentally, and this information is thoroughly covered in the data presented here.

In the thermoelectric properties section, electric conductivity and thermal conductivity graphs, (where available for the same samples) are presented with thermal emf data in order to facilitate calculation of figure of merit values. Cross-referencing of germane information is also provided.

Within the individual properties, arrangement has generally been to show the pure sample data followed by the effects of dopants (in alphabetical order). Doping, per se, however, is often not a qualifying factor, and graphs may be arranged or grouped according to experimental parameters.

In presenting tabular data, values are variously arranged. In some cases, it is by dopant, in others by magnitude of numerical value. On occasion, however, the values from one reference may be grouped for comparison.

The references, from which the data are drawn, are shown by accession number below each graph, with the full bibliographic citation tabulated at the end of the data sheets. The bibliography is listed by accession number.

The electrical conductivity of polycrystalline cadmium oxide, thoroughly annealed, has been measured at 7 to 9 Gc. The thermal energy gap between 20°C and 80°C at these fields agree with those measured in d.c. fields.[9]

According to a recent article in the UKRAINSKYI FIZYCHNYI ZHURNAL,[10] cadmium oxide film has been studied as a transparent contact for cadmium sulfide type photoconductors, both single crystals and films. Volt-ampere and noise characteristics of these cadmium oxide films indicate that it is a good, stable and transparent ohmic contact and is particularly effective for longitudinal photoelectric effects. The cadmium oxide film has a resistivity of about 3×10^{-3} to 6×10^{-3} ohm-cm. This resistivity

is temperature independent from 173°K to 343°X. The advantageous contact characteristics may be attributed to the formation of a cadmium-enriched thin film on the cadmium sulfide surface.

DDC and NASA tapes have been run to assure complete coverage for this material. Very little information is apparently available in the report literature for cadmium oxide.

1 GMELINS HANDBUCH DER ANORGANISCHEN CHEMIE; 8th Ed. Cadmium. Weinheim, Verlag Chemie, GmbH, 1959. p. 418-430.

2 DONNAY, J.D.H. CRYSTAL DATA. DETERMINATIVE TABLES. 2nd Ed. American Crystallography Assoc., 1963.

3 LEMARCHANDS, M. and M. JACOB. Chemical Inertia. SOC. CHIM. DE FRANCE. BULL., v. 5, no. 2, 1935. p. 479-487.

4 HANDBOOK OF CHEMISTRY AND PHYSICS. 46th Ed. Cleveland, Chemical Rubber Publishing Co., 1965-1966.

5 SIDDALL, G. The Preparation of Electroluminescent Panels. VACUUM, v. 7 and 8, 1957-1958. p. 61-71.

6 LUCAS, L.N.D. Oriented Chemical Growth on Single Crystals of Zinc and Cadmium. ROYAL SOC. OF LONDON, PROC., v. 215A, no. 1121, Nov. 25, 1952. p. 162-174.

7 GUDDEN, B. and R. POHL. Lichtelektrische Leitung und chemische Bindung. Z. FUER PHYS., v. 16, 1923. p. 42-45.

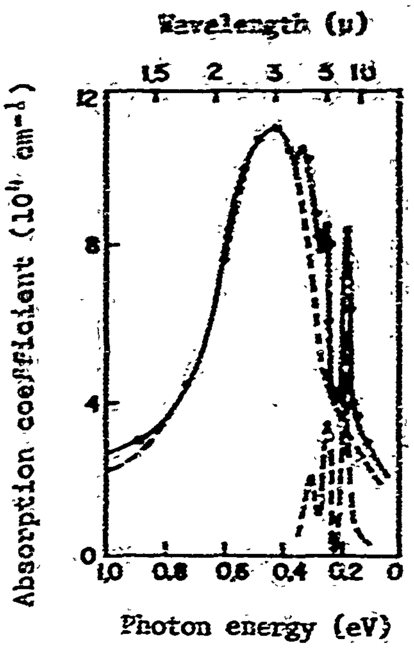
8 FAHRIG, R.H. Growth of Cadmium Oxide Crystals. J. OF APPLIED PHYS., v. 34, no. 1, Jan. 1963. p. 234-235.

9 BALTRUSAITIS and P. BRAZDZIUNAS. Electrical Conductivity of Cadmium Oxide in High-frequency Electric Fields. LIETUVOS FIZ. RINKINYS, LIETUEVOS TSR MOSKLU AKAD., LIETUVOS TSR AUKSTOSIOS MOKYKLOS, v. 4, no. 4, 1964. p. 537-541.

10 SVECHNIKOV, S.V., et al. Ohmic Transparent Contact for 2-6 type Photoconductors. UKR. FIZ. ZH., v. 11, no. 1, 1966. p. 40-44.

CADMIUM OXIDE

ABSORPTION



Absorption coefficient as a function of photon energy for a cadmium oxide film, about 0.1 micron thick, conductivity 1.2 (ohm-cm)$^{-1}$. Fine structure due to electron-photon interactions indicated by peaks corresponding to ionization levels.

—— experimental
.... calculated

Ionization Levels

Electron transition	Energy (eV)
5s--5p^3	0.172
5s--6s	0.295
5s--5p^1	0.248
5s--CB	0.410

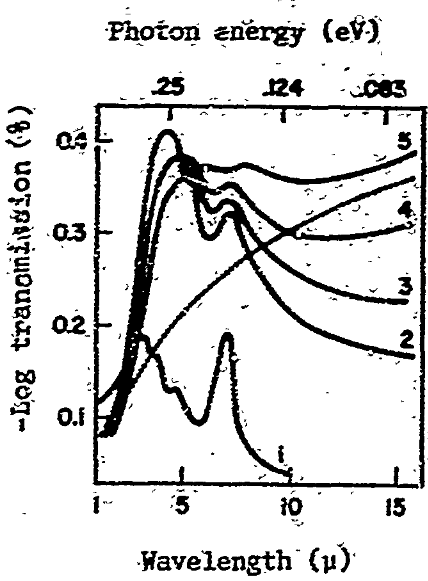
[Ref. 4453]

Log transmission as a function of wavelength in cadmium oxide films of various conductivities.

Film no.	Conductivity (ohm-cm)$^{-1}$
1	0.8
2	35
3	102
4	155
5	255

------free carrier component

The doped films are poor conductors; purifying increases conductivity. The absorption peaks shown are the maximum occupied levels.



[Ref. 4453]

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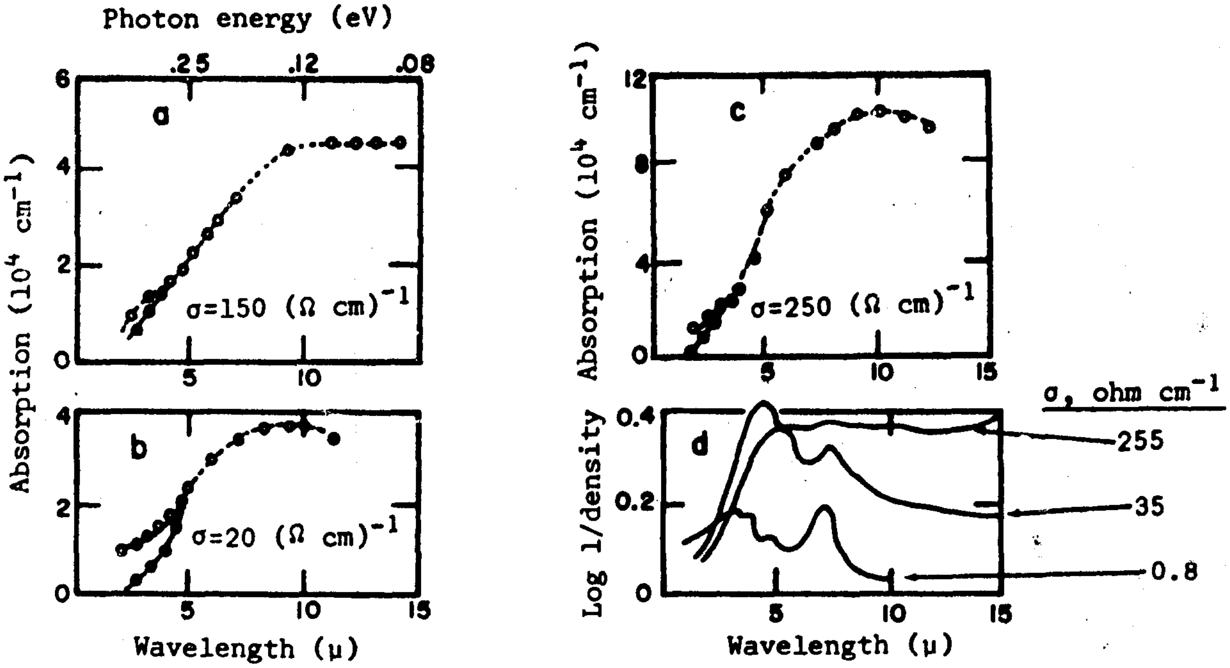


Absorption coefficient as a function of wavelength for cathode sputtered cadmium oxide films. Films in a, b and c are variously prepared on a quartz substrate and variously annealed. Variations in atmosphere and current density during deposition develop films of different electrical conductivity as indicated by the curves.

Films in d are from measurements in [4453] for films deposited on NaCl substrates.

---- Calculated from transmission/incident intensity without correction for reflectivity ($\alpha \sim 1/d \log I_o/I_D$).

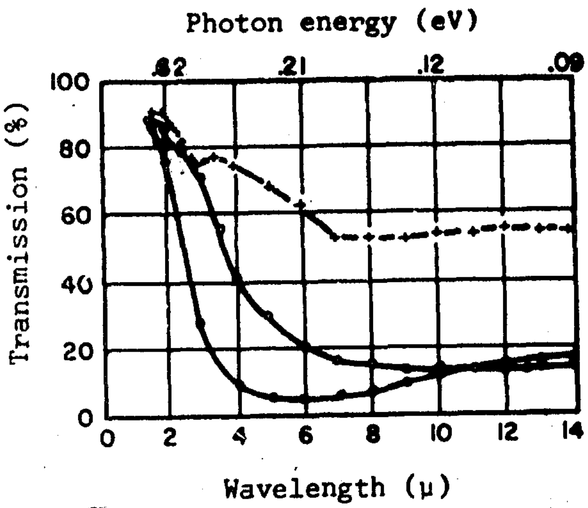
D = transmission
d = film thickness
I_D = transmission intensity
I_o = incident intensity

—— Absorption coefficient calculated from transmission measurements by use of equation for interference for absorbing films.

[Ref. 22103]

CADMIUM OXIDE

ABSORPTION

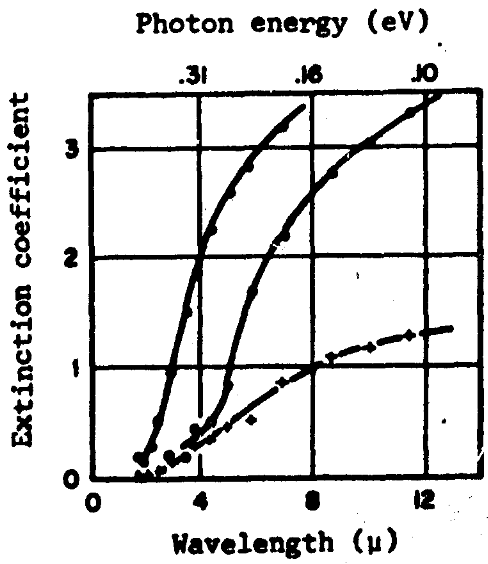


Transmission as a function of wavelength for a cadmium oxide, n-type film 34 microns thick. Preparation is by cathode sputtering in a nitrogen-oxygen atmosphere. The substrate is single crystal sodium chloride. Measurements are made at 300°K. The resulting carrier concentrations after annealing the polycrystalline films are given below:

Curve	Annealing Temperature °C	n_n, (10^{19} cm^{-3})
+	not annealed	1.6
•	160	10.0
o	300	7.0

[Ref. 7151]

Absorption coefficient as a function of wavelength for the same highly degenerate samples as in the above graph. Symbols for curves correspond to those listed above.



[Ref. 7151]

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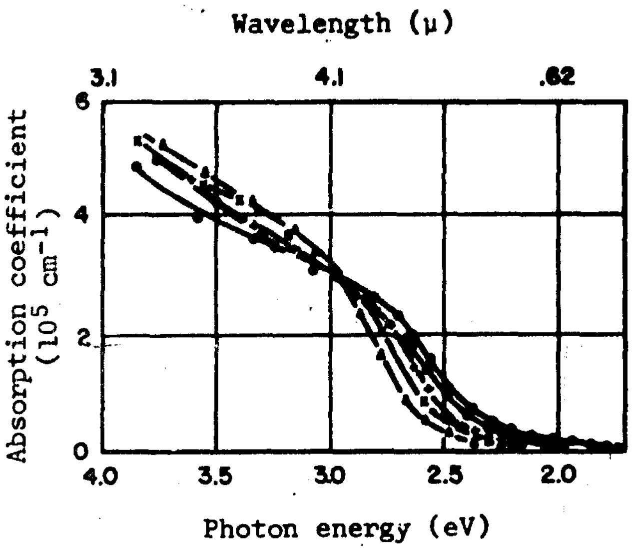


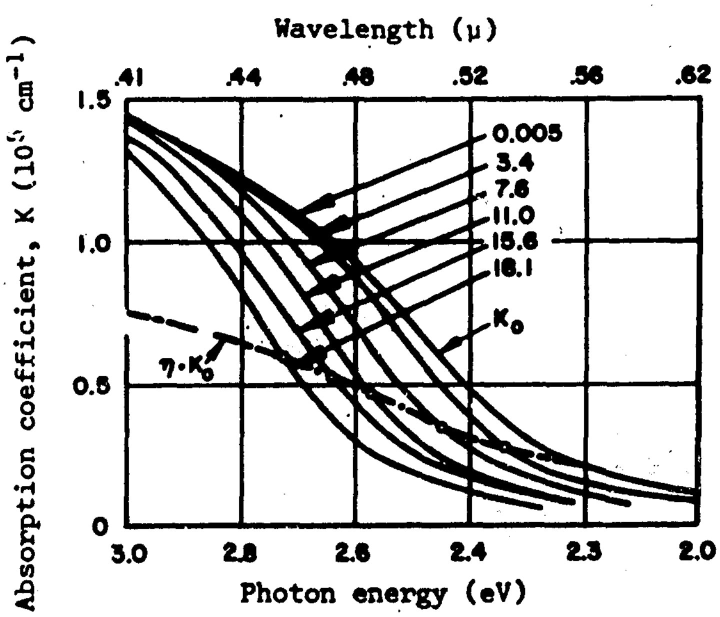
Absorption coefficient as a function of photon energy for several n-type, cathode sputtered cadmium oxide films, between 0.1 and 0.2 microns thick. Measurements are made at 300°K. The films are deposited on a quartz glass substrate and the absorption values are corrected accordingly. Carrier concentrations are given for films after annealing.

Symbol	n_n (10^{19} cm^{-3})
●	1.3
o	5.7
+	9.0
x	15.5
Δ	18.1

[Ref. 20339]

Absorption coefficient at 300°K as a function of photon energy for cathode sputtered cadmium oxide films prepared in a nitrogen-oxygen atmosphere, film thickness 0.12-0.16 microns. Electron concentrations in 10^{19} cm^{-3} are indicated as a parameter of the curves. The intrinsic curve is marked K_o, with $n_n = 5 \times 10^{16}$ cm^{-3}.

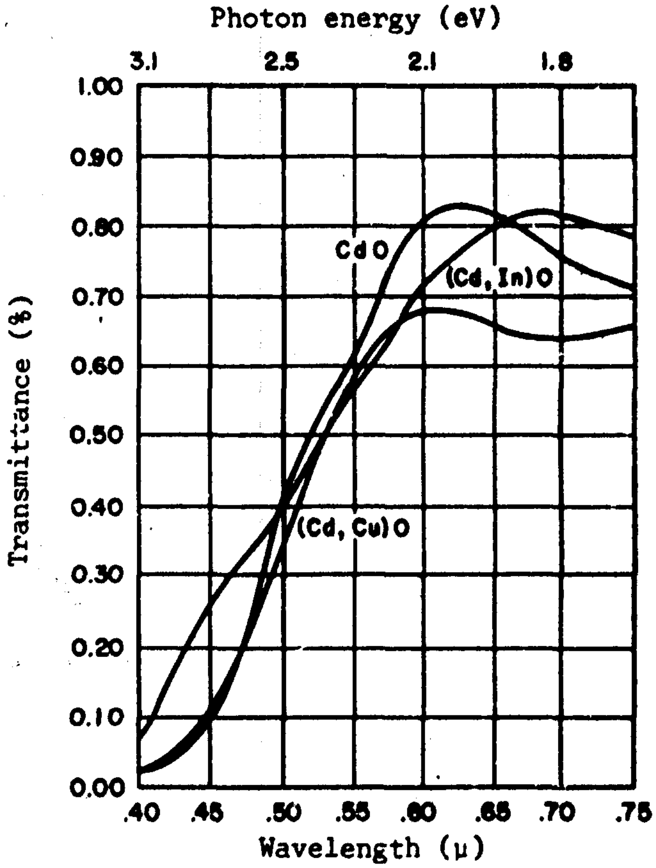
η is the variable ratio K/K_o. By calculating η for a definite range and applying the theoretical curve ηK_o to the family of absorption curves for various carrier concentration values, the theoretical curve cuts the experimental curves at a point which indicates the energy gap. As carrier concentration increases, so does the energy gap.



[Ref. 22102]

CADMIUM OXIDE

ABSORPTION

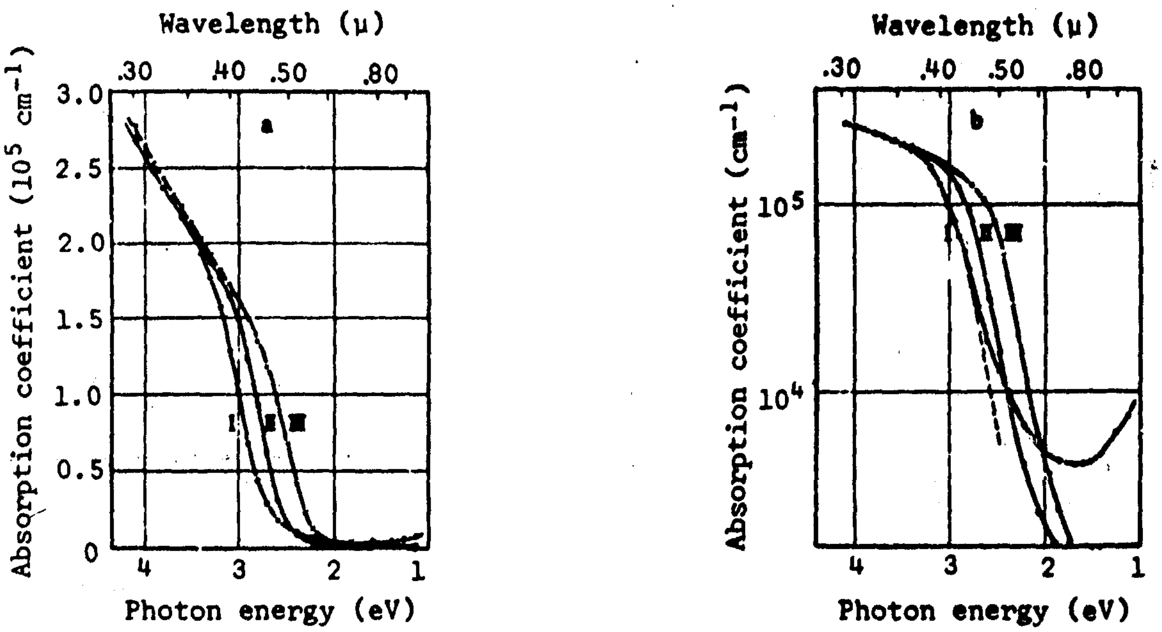


Transmission as a function of wavelength for sputtered cadmium oxide films, all n-type, undoped and doped with copper or indium. Sputtering was done in a 10% oxygen-90% argon atmosphere on optical glass substrates. Film thickness was constant at about 0.28 microns. The undoped film demonstrates a rather diffuse absorption at about 2.5 eV, the reported energy gap. The copper-doped sample shows weak absorption at about 2.1 eV, possibly due to copper, the indium doped sample has a peak as high as the pure sample but at a lower eV.

[Ref. 20405]

CADMIUM OXIDE

ABSORPTION



Absorption coefficient at 300°K as a function of photon energy for cadmium oxide films. The films are prepared by cathode sputtering in nitrogen-oxygen atmosphere.

a) I Not annealed
II Heated 1 hour in air at 200°C
III Heated at 500°C in air

Sample conductivity 10^3 (ohm cm)$^{-1}$	
σ_I	1.52
σ_{II}	1.35
σ_{III}	1.10

b) Same curves plotted to emphasize break in the non-annealed film at ∿1.8 eV.

[Ref. 11868]

CADMIUM OXIDE

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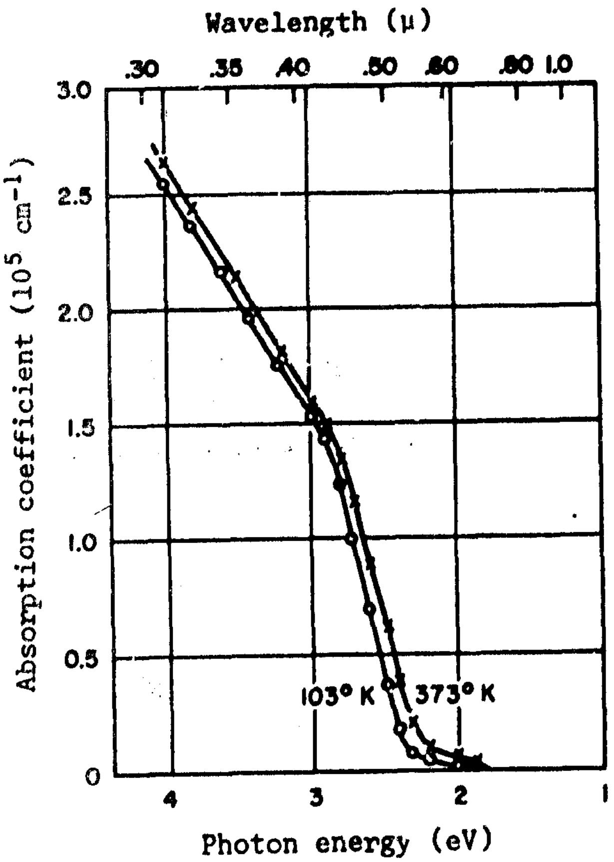

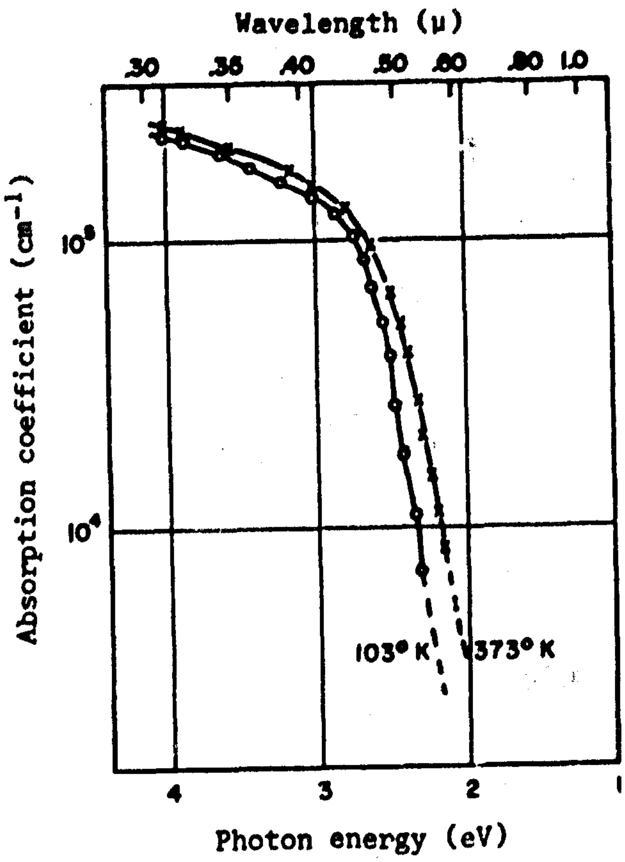

Absorption coefficient as a function of photon energy for a cadmium oxide film prepared at two temperatures. The film was prepared by cathode sputtering in a nitrogen-oxygen atmosphere, and was then annealed in air at 500°C.

Evidently the shift in the absorption coefficient on annealing, leads to a constant value; there is minimum shift during further temperature changes.

[Ref. 11868]

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Dependence of resistivity and transmission of cadmium oxide films on the oxygen content of the discharge gas.

Sputtering Time Mins.	% Oxygen in Argon	Optical Transmission at λ = 5460 Å Baking Before %	After %	Resistivity k Ω per sq. Baking Before	After	Thickness μ
5	100	77	79	18.3	1.96	-
10	100	57	60	9.5	0.545	-
15	100	47	52	5.0	0.315	-
20	100	47	52	4.3	0.288	.0426
5	75	73	78	9.0	1.490	-
10	75	56	60	6.3	0.440	-
15	75	48	53	4.1	0.297	-
20	75	44	50	2.3	0.238	.0509
5	50	78	78	7.9	1.690	-
10	50	56	58	5.0	0.427	-
15	50	50	54	4.8	0.290	-
20	50	44	48	2.3	0.180	.0543
5	25	70	73	9.0	1.150	-
10	25	56	58	1.9	0.436	-
15	25	44	48	1.8	0.182	-
20	25	44	49	1.2	0.134	.0570
10	10	54	53	0.5	0.260	-
20	10	50	52	0.21	0.126	.0509
10	5	64	66	1.2	0.520	-
20	5	60	59	0.103	0.110	.0644

Note: The above films were sputtered at 3 kV and 0.3 mA/cm from a 45 cm diameter cathode at a distance of 10 cm.

[Ref. 15410]

CADMIUM OXIDE

DEBYE TEMPERATURE

Value θ, °K	Electrical Resistivity (10^{-3} ohm cm)	Sample	Carrier Concentration n_n (10^{20} cm^{-3})	Temp. °K	Ref.
560	1.8	sintered powder	10	20-25	3070
450	2.3	"	8	1-250	
680	29	"	23	100-250	
800-1000	1.3	highly compressed and sintered powder	7	100-700	

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DIELECTRIC CONSTANT

Symbol	Value	Sample	Test Method	Temp.	Ref.
ε_∞	5.6	CdO cathode sputtered films, annealed $n_n = 1.4$ to 9×10^{19} cm^{-3}	optical absorption measured	300°K	22103†
	6.2	powder	oil immersion $\lambda = .6708\ \mu$	300°K	Ksanda*

ε_∞ is the optical dielectric constant and is calculated from the refractive index.

*KSANDA, C.J. Comparison Standards for the Powder Spectrum Method - Nickel Oxide and Cadmium Oxide. AMERICAN J. OF SCI., v. 22, 1931. p. 131-138.

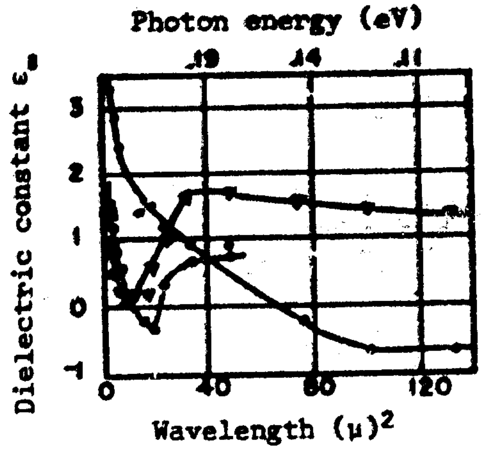
† page 525

CADMIUM OXIDE

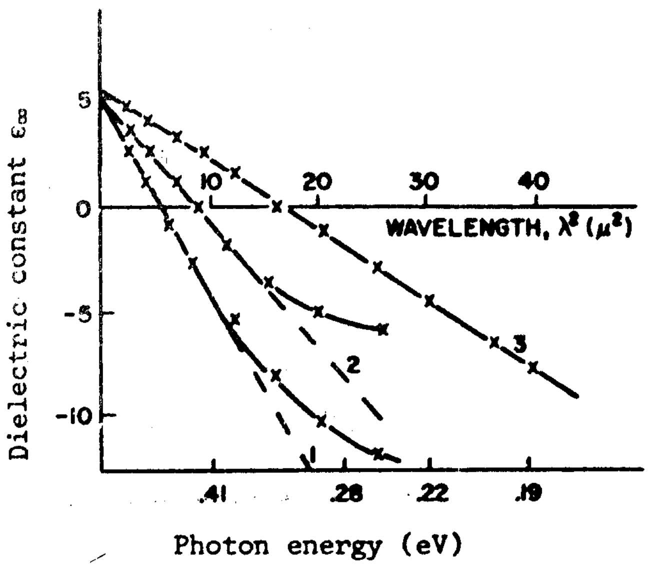
DIELECTRIC CONSTANT

Three curves showing the optical dielectric constant, as a function of the square of the wavelength. The 34 microns thick film is prepared by cathode sputtering in a nitrogen-oxygen atmosphere.

Curve	Annealing Temp. °C	Carrier Concentration n_n (10^{19} cm^{-3})
+	not annealed	1.6
●	160	10.0
o	300	7.0



[Ref. 7151]



Dielectric constant as a function of photon energy in sputtered cadmium oxide films, 0.2-1 micron thick.

Sample	Carrier Concentration n, (10^{20} cm^{-3})
1	12.1
2	6.55
3	1.32

λ^2 $(\mu)^2$	λ (μ)	eV
10	3.2	.39
20	4.5	.28
30	5.5	.23
40	6.3	.19

[Ref. 5183]

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EFFECTIVE MASS (m*)

Sample No.	55	56	57	50	Temp. °K
Hall coefficient (10^{-9} cm^3/coul)	2.4	3.7	16.5	30.3	300
Thermoelectric power (μV/°K)	.090	.103	.174	.214	500
Effective mass m^*/m_o	0.10	0.11	0.15	0.15	300

[Ref. 10904]

Sample No.	36	22	15	7	20	35	Temp. °K
Sintering time (hours)	0.5	0.5	0.5	24.0	0.5	0.5	
Sintering temperature (°K)	1200	1000	930	920	1100	1200	
Hall coefficient (to 6 kOe) (10^{-9} cm^3/coul)	14.5	17.0	20.5	3.6	2.5	5.6	300
Electron carrier concentration (10^{18} cm^{-3})	4.3	3.6	3.1	17.4	25.0	11.2	
Temperature coefficient of resistance (10^{-5} ohm cm/deg.)	11.3	18.0	13.9	3.7	1.4	4.3	
Effective mass m^*/m_o	0.05	0.08	0.05	0.08	0.06	0.06	

[Ref. 10904]

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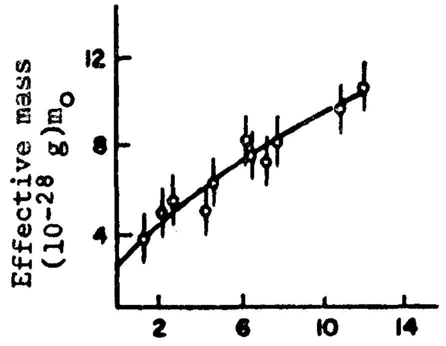
CADMIUM OXIDE

EFFECTIVE MASS (m*)



Electron effective mass as a function of carrier concentration in cathode sputtered cadmium oxide films 0.2 to 1 microns thick. Carrier concentration varies from 1 x 10^{20} to 12 x 10^{20} cm^{-3}, measurements made at 300°K.

[Ref. 5183]

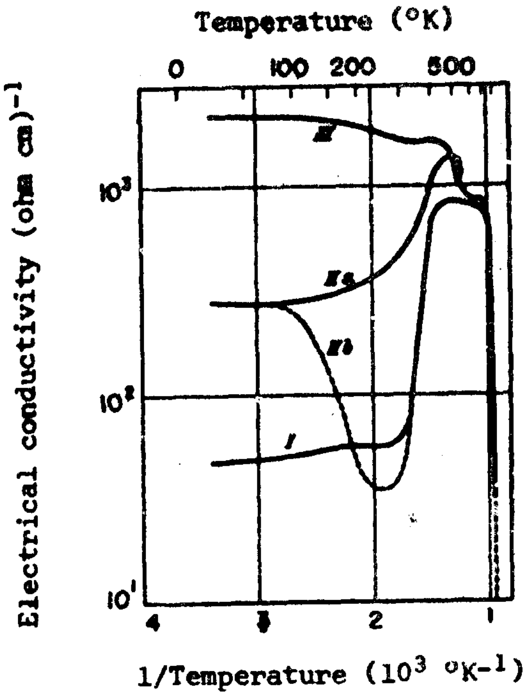
Symbol	Value	Sample	Test Measurement	Temp.	Ref.
m_n	0.16 0.14	film, n = 1.25 x 10^{20} cm^{-3}	optical absorption, λ = 1-2.5 microns	113 & 293°K	17670
m_n	0.14	cathode sputtered films. annealed at 500°C. n ≈ 5 to 50 x 10^{20} cm^{-3}	electrical conductivity, Hall and thermal emf measurements, also optical absorption	20- 750°C	22103

CADMIUM OXIDE

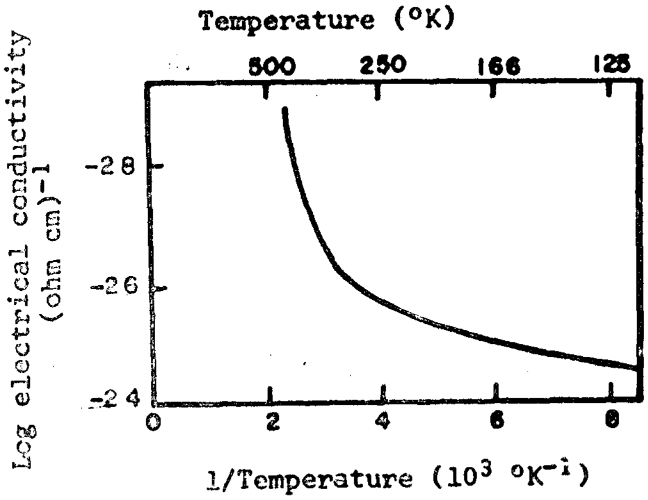
ELECTRICAL CONDUCTIVITY

Electrical conductivity as a function of reciprocal temperature for cadmium oxide films. Curves are non-reversible.

- I Cathode sputtered in oxygen, annealed in air.
- II_a Cathode sputtered in air, annealed in vacuum.
- II_b Annealed in air.
- III Cathode sputtered in nitrogen-low oxygen atmosphere.



[Ref. 3926]



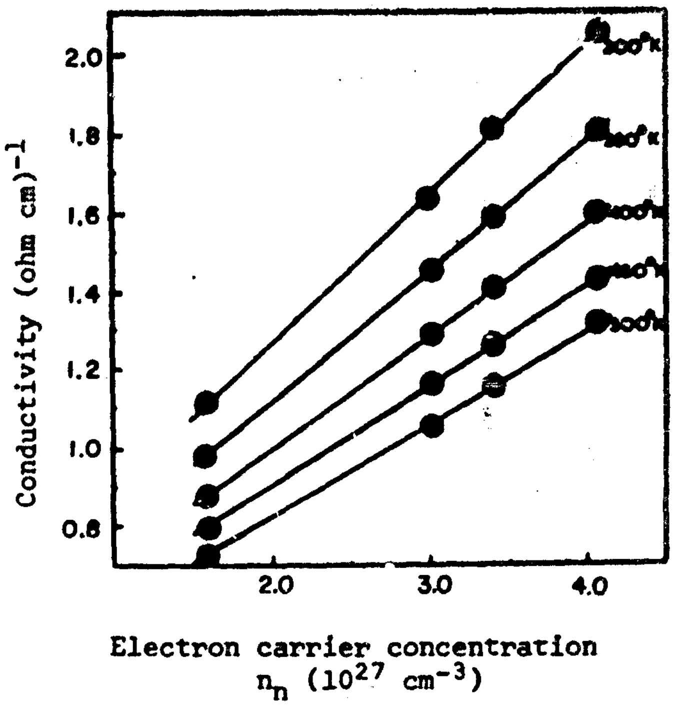
Log electrical conductivity as a function of reciprocal temperature for cadmium oxide powder samples compressed at 1000 kg/cm^2 and treated with oxygen.

[Ref. 12730]

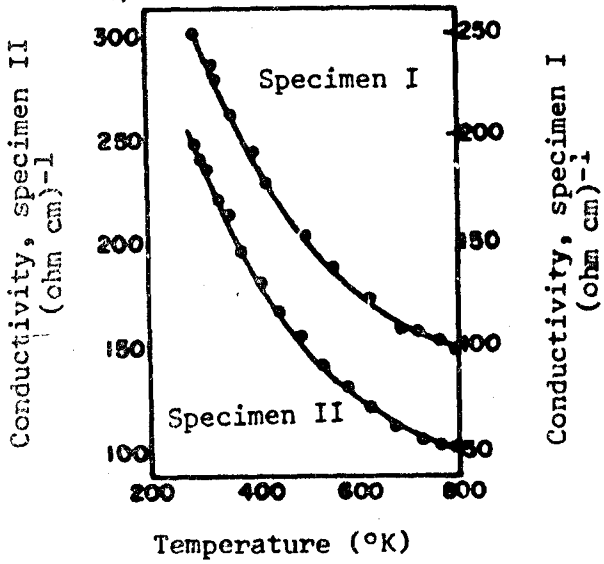
CADMIUM OXIDE

ELECTRICAL CONDUCTIVITY

Electrical conductivity as a function of free electron concentration, expressed as $n_n^{4/3}$ (10^{27} cm^{-3}). The temperature parameter of the curve is shown on the graph. The samples are sintered cadmium oxide pellets. Slope of conductivity against $n^{4/3}$ is linear in keeping with the Howorth and Sondheimer theory.



[Ref. 20243]



Electrical conductivity as a function of temperature for two pressed and sintered cadmium oxide strips.

Specimen	Carrier Concentration $n(10^{20}$ $cm^{-3})$
I	7.5
II	5.5

[Ref. 2189]

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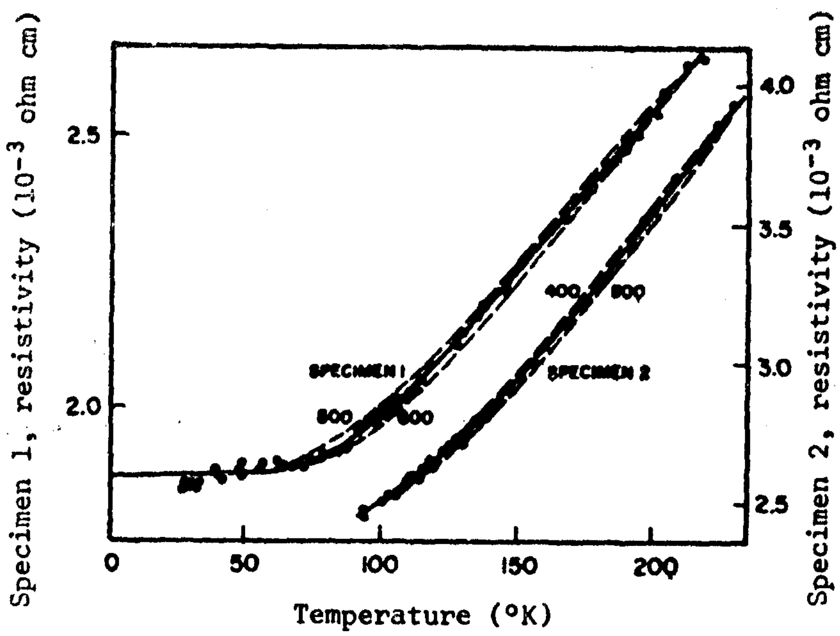
CADMIUM OXIDE

ELECTRICAL RESISTIVITY



Electrical resistivity as a function of temperature for two pressed sintered cadmium oxide strips. The solid lines are derived from values of ρ_o, A, and θ chosen to give the best possible graphical agreement in the formula: $\rho\ \rho_o + \frac{1}{AT \sinh^2 (\theta/2T)}$. The expression for neighboring values of θ are shown as broken lines. A is the temperature coefficient of conductivity and varies with the impurity concentration of each sample.

Temp. Range (°K)	Specimen	Carrier Concentration n (10^{20} cm^{-3})	ρ_o (ohm cm)	θ (°K)	A $(ohm\ cm)^{-1}$/deg
20-250	1	10	.0018	560	2.5
1-250	2	8	.0023	450	2.0

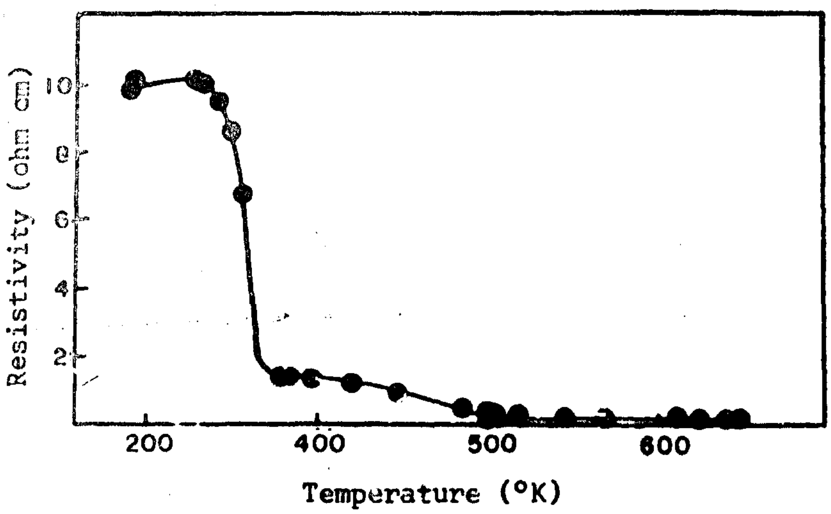
——— calculated

----- Debye values

[Ref. 3070]

CADMIUM OXIDE

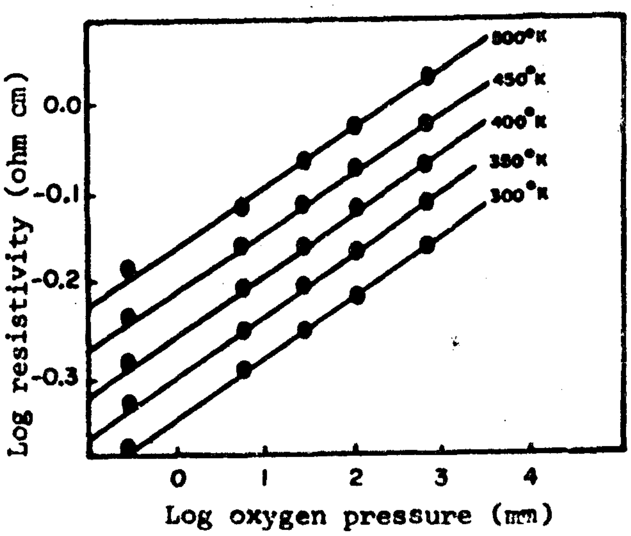
ELECTRICAL RESISTIVITY



Electrical resistivity as a function of temperature during sintering for pressed cadmium oxide pellets. Sintering is accomplished at 1 atm. oxygen. From 340-380°K the sharp drop in resistivity is believed due to increased contact of the microcrystals.

[Ref. 20243]

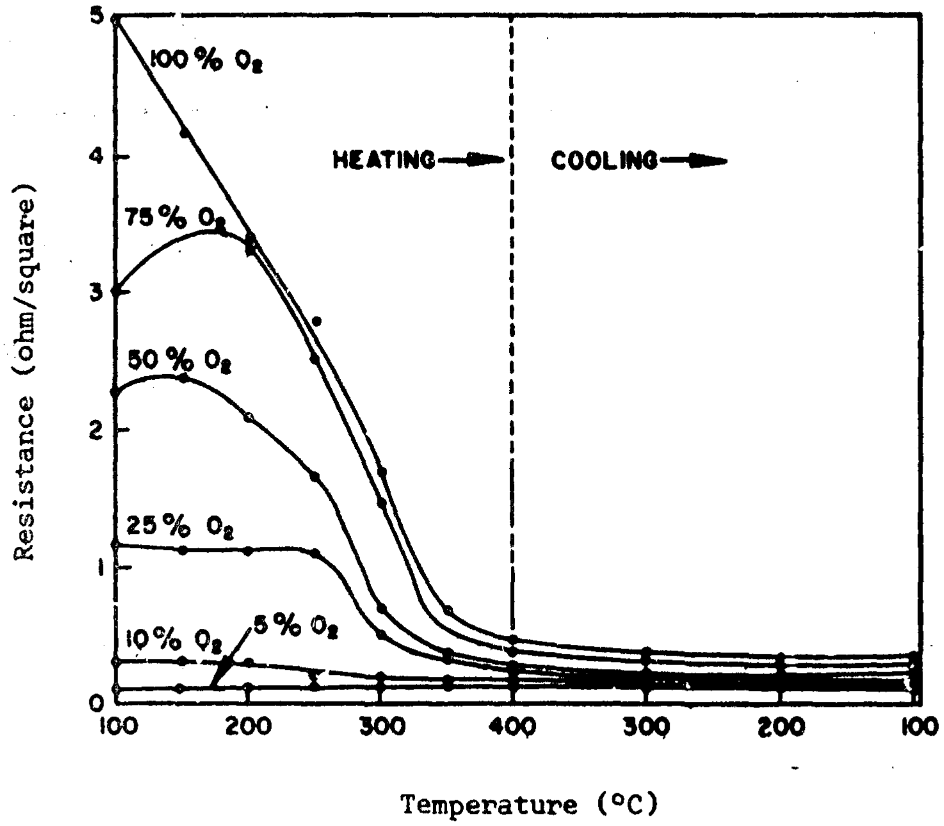
Log electrical resistivity as a function of log oxygen pressure for pressed and sintered cadmium oxide pellets. Data taken at temperatures indicated on the curves.



[Ref. 20243]

CADMIUM OXIDE

ELECTRICAL RESISTIVITY



Resistance of cadmium oxide films upon annealing and cooling. Cycle from 100→400→100°C over 75 minutes. Curves are given for films produced in different oxygen/argon mixtures.

The films are cathode sputtered in an oxygen-argon atmosphere on glass substrates for 20 minutes; thickness is about 0.06 micron.

Control of oxygen content at 5% yields consistently high-conductivity films on low temperature substrates.

[Ref. 15410]

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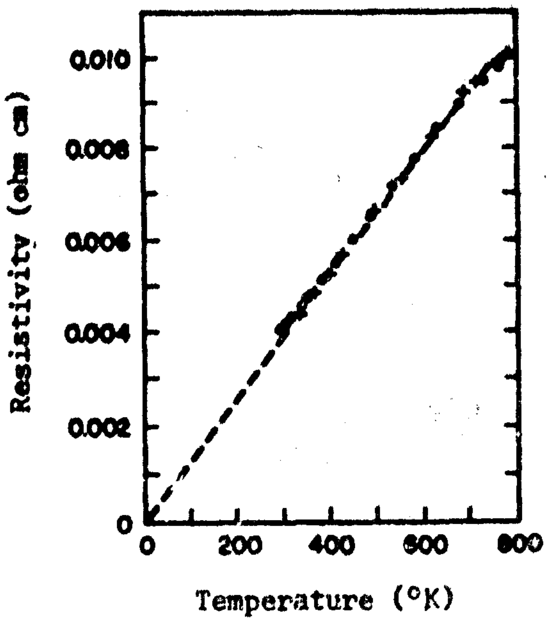
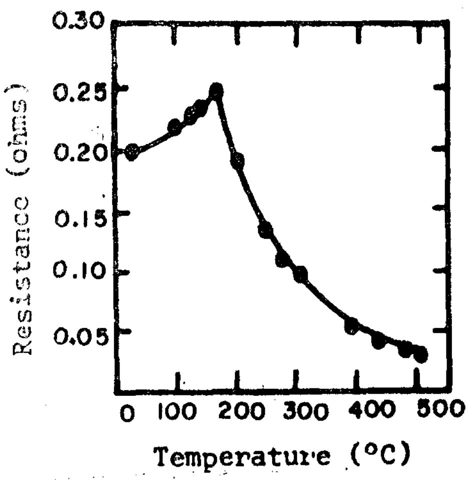
CADMIUM OXIDE

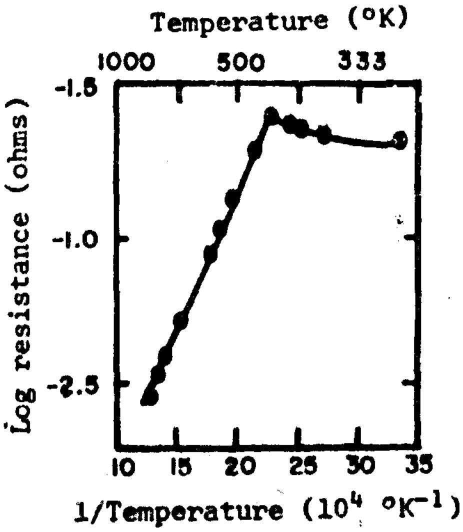
ELECTRICAL RESISTIVITY

Electrical resistivity as a function of temperature for two pressed sintered cadmium oxide strips. Carrier concentration is $>10^{20}$ cm^{-3}.



[Ref. 2189]





Resistance as a function of reciprocal temperature for pressed powder cadmium oxide. The high temperature curve is linear with an activation energy of 0.40 eV.

[Ref. 11654]

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CADMIUM OXIDE

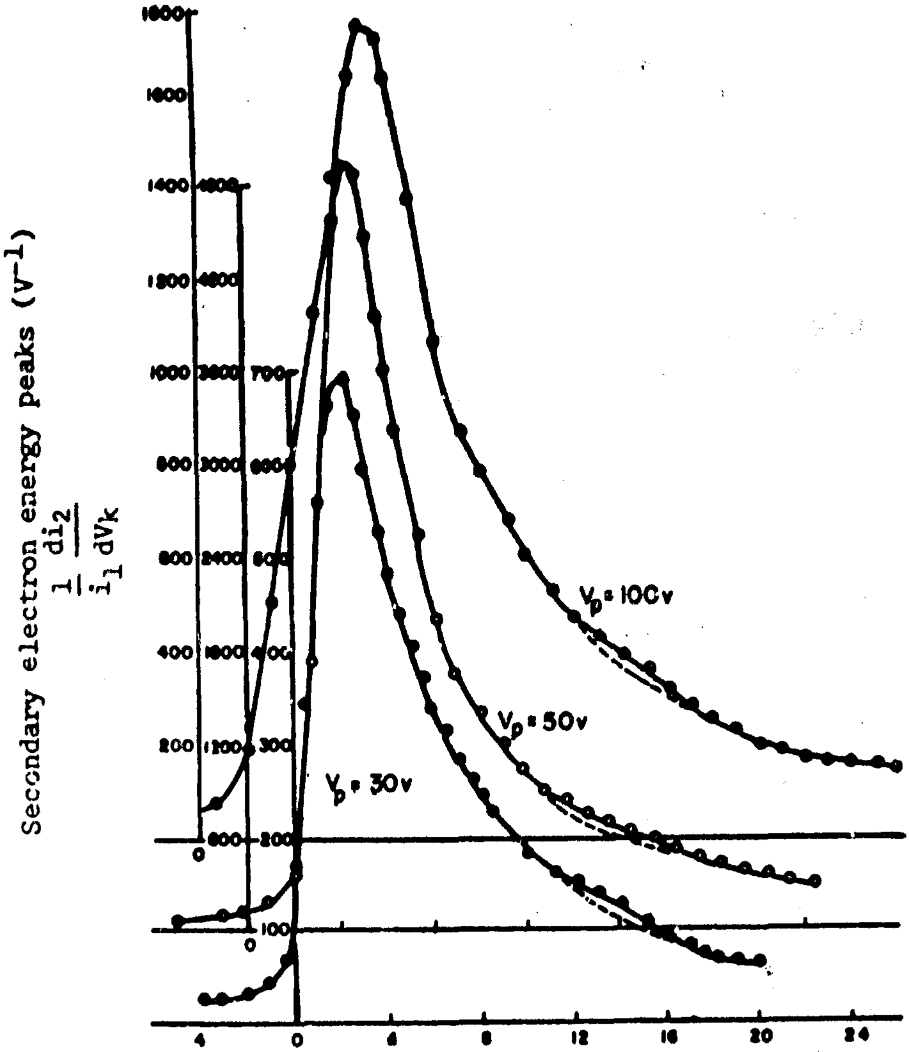
ELECTRON SECONDARY EMISSION

Energy distribution of the secondary electrons as a function of the discrete electron energy loss at 250°C. The curves are obtained from data taken on a 0.5 mm thick cadmium oxide disc, resistivity at 300°K = 0.027 ohm cm. The primary electron energy V_p is shown on each curve.

V_k is the collector voltage

i_1 is the initial current

i_2 is the secondary current

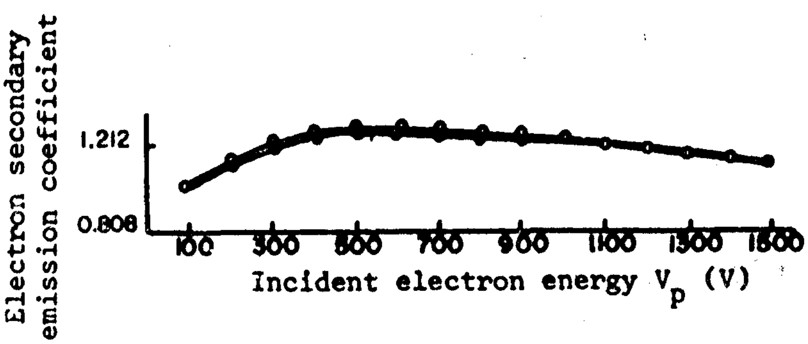


[Ref. 23133]

Electron secondary emission coefficient as a function of incident electron energy for same sample.

o 20°C
• 400°C

Maximum value is 1.25 at 400 volts and varies little with temperature.



[Ref. 23133]

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CADMIUM OXIDE

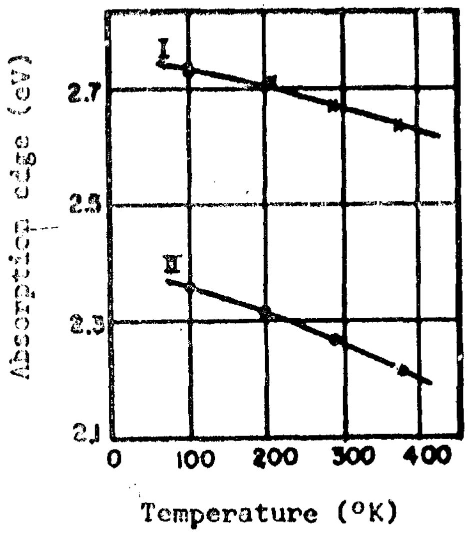
ENERGY BANDS

Symbol	Change in Energy Gap with Temperature, eV/°K (10^{-4})	Sample	Temp. °K	Ref.
dEg/dT	-3.3	Film, $n = 8 \times 10^{16}$	113-293	17670
	-4	*Cathode sputtered film deposited in nitrogen/low oxygen atmosphere	200-400	11868
	-6	*Same film annealed at [illegible]00°C	"	"
	-2.6 to -5	Single crystal $n = 7 \times 10^{19}$ cm^{-3} $\sigma = 1.3 \times 10^{3}$ $(ohm\text{-}cm)^{-1}$	98-295	20385

* See page 26 for source absorption measurements.

CADMIUM OXIDE

ENERGY BANDS



Shift in the absorption edge with temperature for two cadmium oxide films.

I. This film prepared in nitrogen with low oxygen.

II. Same cathode-sputtered film after annealing at 500°C. The absorption edge is measured at that wavelength for which the absorption constant is 2×10^4/cm. This wavelength varies with temperature but is about .56 micron or 2.2 eV. (This is close to the energy gap of 2.35 eV, given in this reference.)

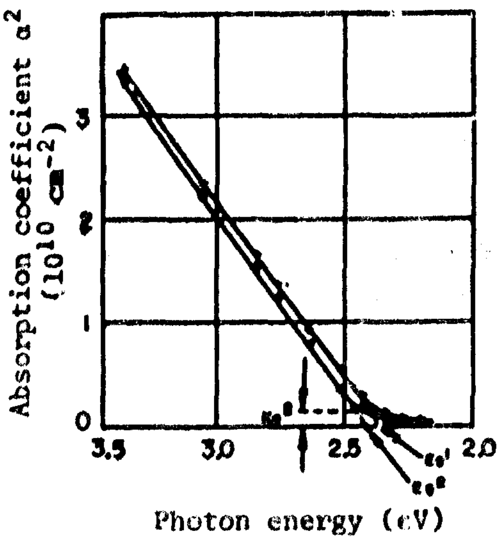
[Ref. 11868]

Square of the absorption coefficient as a function of photon energy for a cadmium oxide film at five temperatures between 113 and 293°K. The carrier concentration is 8×10^{16} cm^{-3}.

Eg^1 is energy gap at 293°K

Eg^2 is energy gap at 113°K

K_o^2 is the absorption edge at 0°K



[Ref. 17670]

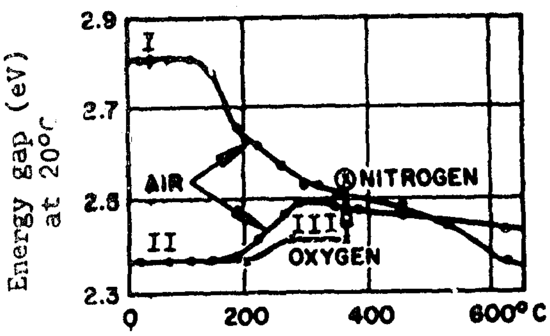
CADMIUM OXIDE

ENERGY GAP (Eg)

Value (eV)	Sample Specification	Test Method	Temp. °K	Ref.
2.51	single crystal, $\sigma = 1.3 \times 10^3\ (\Omega\ cm)^{-1}$, $n = 7 \times 10^{19}\ cm^{-3}$	reflectivity	295	20385
2.56	"		98	
2.35	single crystal, annealed 28 hrs. at 600°C in oxygen, $\sigma = 1.05 \times 10^2\ (\Omega\ cm)^{-1}$, $n = 1.3 \times 10^{18}\ cm^{-3}$		295	
2.41	"		98	
~2.3	films cathode sputtered 0.1 - 0.2 micron thick, $n = 10^{19} - 1.8 \times 10^{20}\ cm^{-3}$	reflectivity 0.3-0.8 micron	0	20339
2.35	cathode sputtered films in oxygen or nitrogen, annealed in oxygen	reflectivity	300	11868

CADMIUM OXIDE

ENERGY GAP



Temperature (°C)

Energy gap at 20°C as a function of one hour annealing at temperature indicated on abscissa for sputtered cadmium oxide films prepared in:

o I. Nitrogen-low oxygen atm.

• II. Pure oxygen atm.

Curve I is annealed in air which causes the energy gap to shift from 2.81 to 2.36 eV. Curve II is annealed in air. This raises the absorption edge.

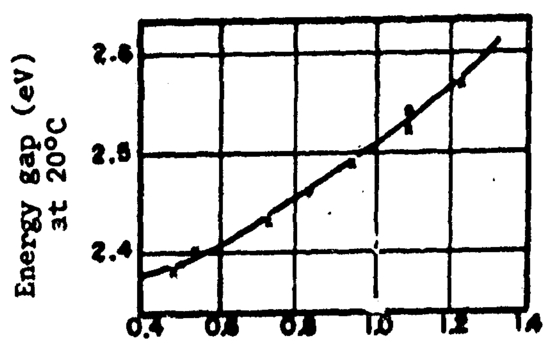
Curve III (x) is the same film as in curve II, annealed in pure oxygen. Here, also, the absorption edge is raised.

If the film in Curve III is then annealed for 1 hour in nitrogen, the energy gap is again considerably increased.

[Ref. 11868]

Absorption edge at 20°C as a function of electrical conductivity at 20°C for a cathode sputtered cadmium oxide film annealed in air between 400 and 600°C followed by annealing at 350°C in nitrogen, oxygen or a vacuum. All measurements fall on the same curve.

Annealing above 350°C causes an increase in conductivity and an energy gap increase. A decrease in conductivity is connected with a shift in energy gap toward higher wavelengths (i.e., lower energy gap).

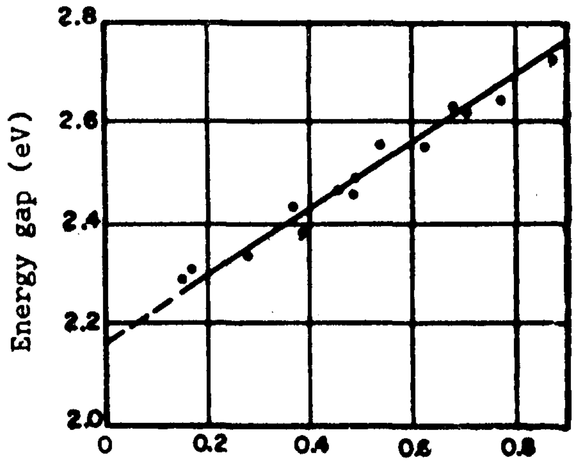


Electrical conductivity at 20°C (10^3 Ω^{-1} cm^{-1})

[Ref. 11868]

CADMIUM OXIDE

ENERGY GAP



Energy gap as a function of the Fermi level in cathode sputtered cadmium oxide films, prepared in a nitrogen - oxygen atmosphere. Film thickness 0.12-0.16 micron. Electron carrier concentration = 10^{16} to 2×10^{20} cm^{-3}. Absorption data taken at 0.3 - 0.8 micron. The curve shown is calculated for a limiting energy gap value of 2.2 eV. Fermi level values are calculated from electron carrier concentration using $m_n^* = 0.14\ m_o$.

As the carrier concentration in the samples increases, the Fermi level shifts away from the conduction band with accompanying increase in energy gap.

[Ref. 22102

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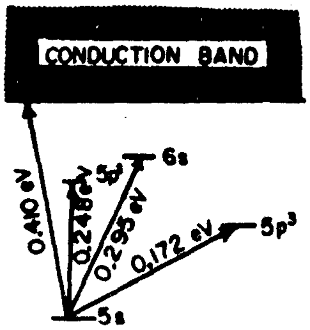
CADMIUM OXIDE

ENERGY LEVELS

Symbol	Value (eV)	Sample	Temp.	Ref.
E_F	0.6→0.3	Decrease in Fermi level as cadmium content increases with temperature in a sintered powder $n \sim 10^{18}$ cm^{-3}.	800°C	20243
E_D	0.4 CB	Pressed powder, excess cadmium		11654

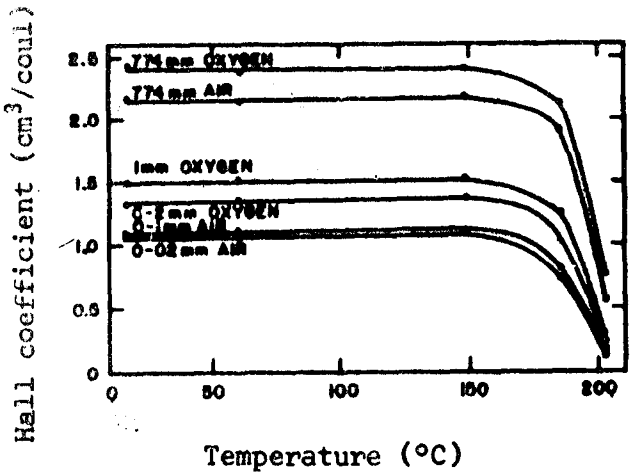


Energy levels for a cadmium oxide film about 0.1 micron thick; indicated by optical absorption peaks. (See page 5 for graph of absorption coefficient showing four structure peaks corresponding to various ionization levels.

[Ref. 4453]

CADMIUM OXIDE

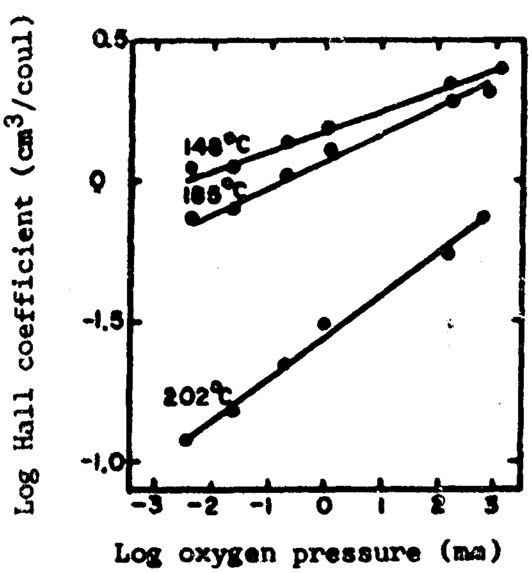
HALL COEFFICIENT



Hall coefficient as a function of temperature for cadmium oxide at different air and oxygen environments.

[Ref. 5248]

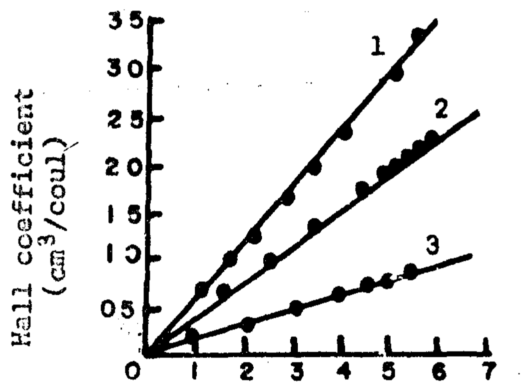
Hall coefficient as a function of oxygen pressure for n-type, compressed powder cadmium oxide; $n \sim 3.4 \times 10^{18}$ cm^{-3}.



[Ref. 5248]

CADMIUM OXIDE

HALL COEFFICIENT



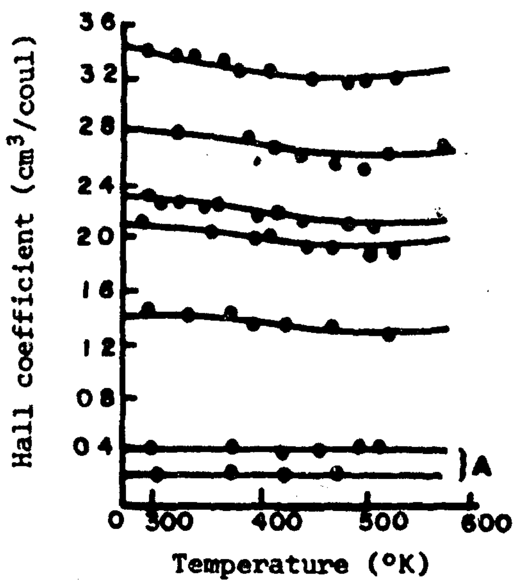
Variation of the Hall coefficient with magnetic field for three cadmium oxide pellets at 300°K. The samples are pressed powder, sintered at 600-1200°K. Electron carrier concentrations are 2×10^{18} to 4×10^{19} cm^{-3}.

In general, the Hall coefficient increases with decrease in electron carrier concentration, i.e., curve 1 would be for the sample with the lowest n_n.

[Ref. 10904]

Variation with temperature of the Hall coefficient for specimens of differing electron concentration. Experimental points are shown in close conformity to curves drawn from theoretical considerations assuming $m^* = 0.3\ m_o$ and the characteristic temperature of the longitudinal optical phonons is 500°K.

Compressed cadmium oxide powders, sintered at 600-1200°K, $n = 2 \times 10^{18}$ to 4×10^{19} cm^{-3}. A indicates two curves for highest carrier concentrations.



[Ref. 10904]

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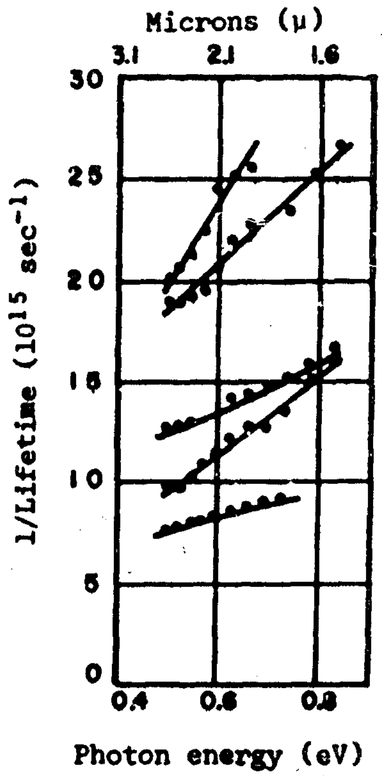
CADMIUM OXIDE

LIFETIME (τ)

Lifetime, (10^{-15} sec)	Sample Specifications	Method	Temp. °K	Ref.
4.5	film, $n_n = 1.25 \times 10^{20}$ cm^{-3}	optical absorption at 0.35 to 0.6μ	113-293	17670
1.5 to 4.0	cathode sputtered films, $n_n = 10^{19}$ to 10^{20} cm^{-3}	optical transmission λ = 1 to 14μ	300	7151

Reciprocal average electron lifetime as a function of photon energy in cathode sputtered polycrystalline cadmium oxide films annealed at 450°C. Lattice defects are removed by annealing to 500°C; $n_n = 5 \times 10^{19}$ to 5×10^{20} cm^{-3}. Further sample characteristics are not given. The curves are linear and are calculated from refractive index and absorption measurements. The experimental points are data for several varied films. The wavelength region is narrow because at 1.5 micron intrinsic absorption sets in and at 2.5 micron the experiment becomes inoperable.



[Ref. 22103]

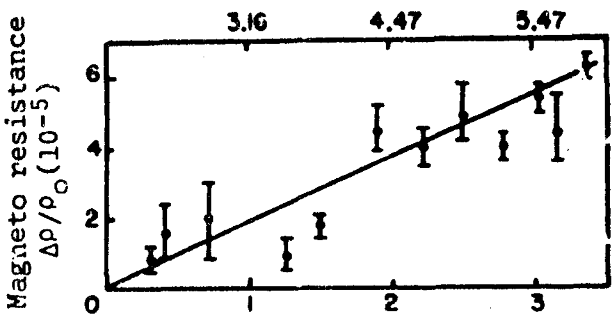
CADMIUM OXIDE

MAGNETIC SUSCEPTIBILITY

Magnetic Susceptibility χ (10^{-6} cgs)	Sample Specifications	Temp. °K	Ref.
-0.2320	highly purified powder	300	7119

CADMIUM OXIDE

MAGNETOELECTRIC PROPERTIES



Magneto-resistance as a function of magnetic field for sintered polycrystalline cadmium oxide at 300°K. Each point indicates mean of 20 observations in samples with $n = 10^{18}$ to 10^{19} cm^{-3}.

Sample No.	60	61	48
$\Delta\rho/\rho_o$ (x 10^5) at 5.8 kOe	5.2	4.7	2.9
Electron carrier concentration (10^{18} cm^{-3})	2.8	3.6	11.2

[Ref. 10904]

CADMIUM OXIDE

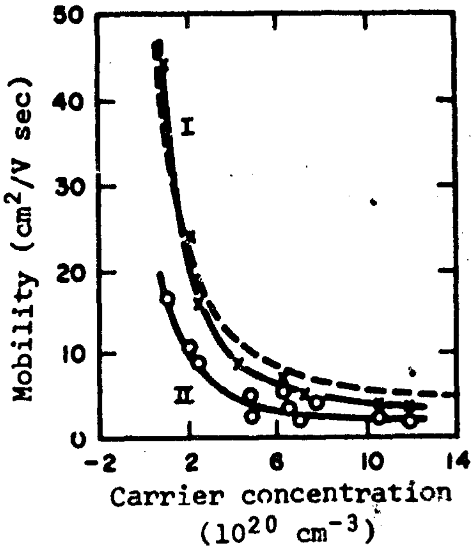
MOBILITY (μ)

Mobility as a function of electron carrier concentration in cathode sputtered films, 0.2-1 micron thick. Optical data at 300°K in the infrared (1.5-7 microns).

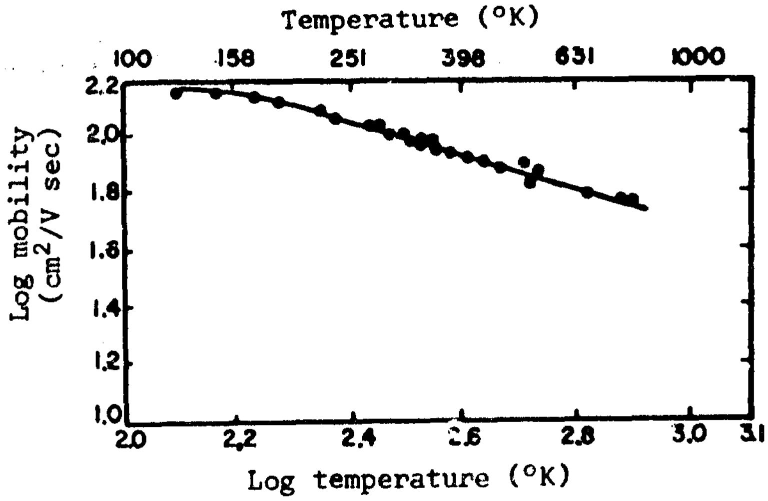
------ calculated from Conwell-Weisskopf formula for mobility of degenerate semiconductors

I experimental curve from optical data

II experimental curve from electrical data ($\mu = R_H\sigma$). Discrepancies due to high resistance transition layers in polycrystalline films



[Ref. 5183]



Mobility as a function of log of temperature. Crystalline cadmium oxide, $n \sim 10^{18}$ to 10^{19} cm^{-3}, H = 7400 Oe.

[Ref. 8798]

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Electrical Properties of n-type Doped and Undoped Cadmium Oxide Films at 300°K

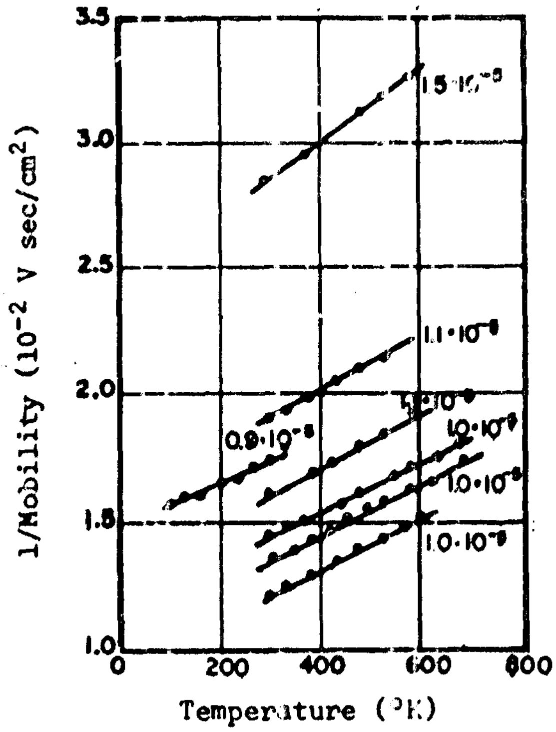
Hall Mobility, cm^2/V sec	Cathode	Atmosphere Argon:Oxygen	Film Thickness, Å	Ohms/ Square	Conductivity, σ, $(ohm\ cm)^{-1}$	Hall Constant, R_H, $cm^2/coul$
7.9	Cd	98:2	2430	88	467	0.017
5.0		95:5	1850	490	110	0.045
4.2		90:10	2030	590	83	0.051
0.16		0:100	1390	22,400	0.64	0.251
3.2	95 Cd-5 Cu	98:2	2430	390	106	0.030
"	"	95:5	2620	800	48	0.067
2.4	"	90:10	2810	1,500	24	0.101
2.3	95 Cd-5 In	99:1	2810	188	189	0.012
1.7		98:2	2250	240	131	0.013
2.2		95:5	1690	466	127	0.017
2.1		90:10	1390	630	117	0.018

[Ref. 20405]

Hall Mobility, cm^2/V sec	Sample Specifications	Method	Temp. °K	Ref.
20 to 50	cathode sputtered films; $n_n = 10^{19}$ to 10^{20} cm^{-3}	optical transmission λ = 1 to 14 microns	300	7151

CADMIUM OXIDE

MOBILITY (μ)



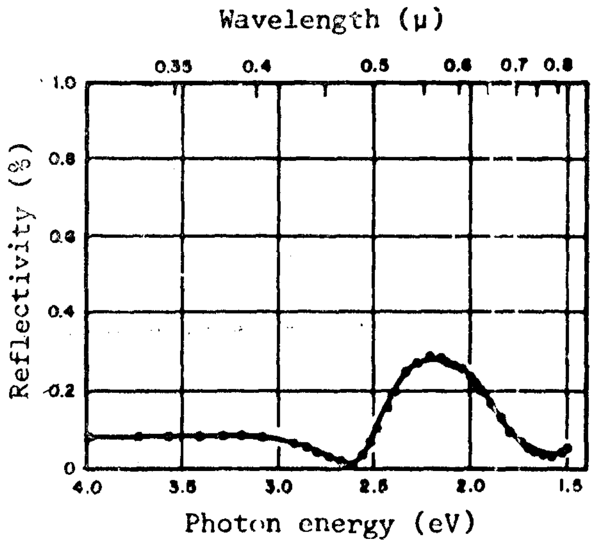
Reciprocal electron mobility as a function of temperature in cathode sputtered cadmium oxide films, annealed at 450°C, $n \sim 5 \times 10^{19}$ to 5×10^{20} cm^{-3}. The temperature coefficient of mobility is almost constant as indicated on the curves. The lattice mobility is calculated to be 220 cm^2/V sec at 300°K.

[Ref. 22103]

CADMIUM OXIDE

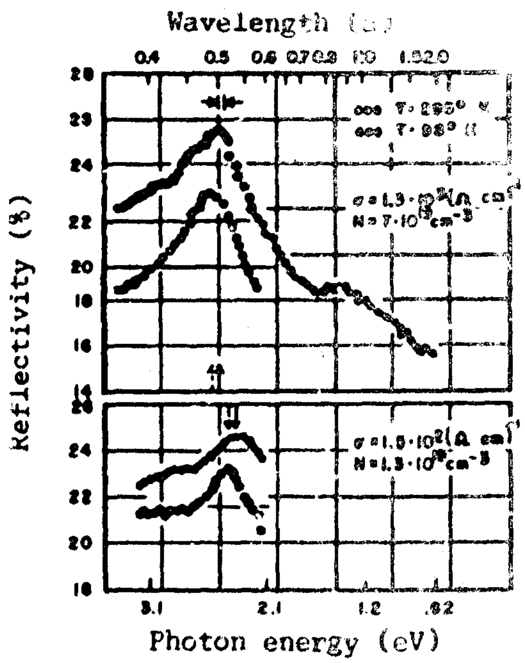
REFLECTIVITY

Reflectivity as a function of wavelength for various cadmium oxide samples, all measured at 300°K.



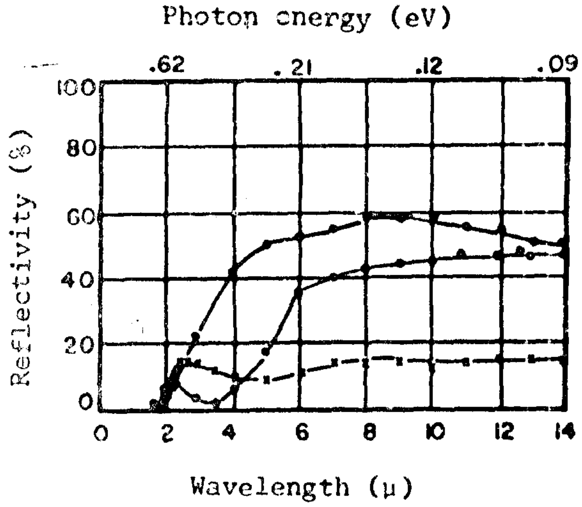
Cathode sputtered, n-type films, 0.183 microns thick, $n = 15.5 \times 10^{19}\ cm^{-3}$.

[Ref. 20339]



Single crystal samples. Temperature, carrier concentration and conductivity are given.

[Ref. 20385]



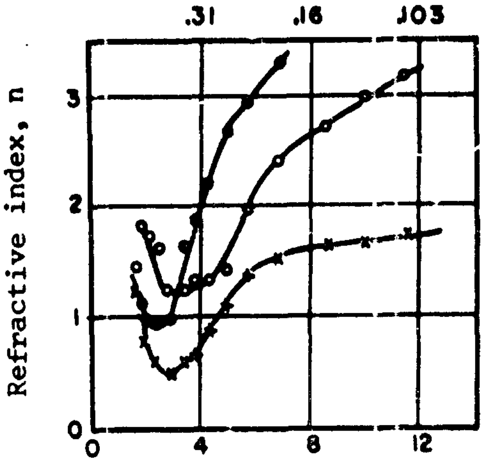
Cathode sputtered film, 34 microns thick.

Symbol	Treatment	n_n (10^{19} cm^{-3})
+	untempered	1.6
•	annealed at 160°C	10
○	annealed at 300°C	7

[Ref. 7151]

CADMIUM OXIDE

REFRACTIVE INDEX (n)



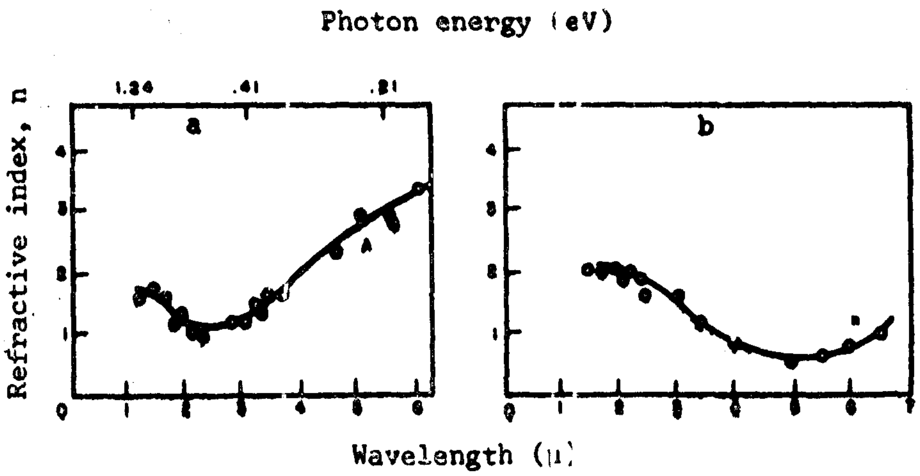
Refractive index as a function of wavelength for a cathode sputtered film of cadmium oxide, at 300°K. Film is 34 micron thick.

Symbol	Treatment	n_n (10^{19} cm^{-3})
+	untempered	1.6
●	annealed at 160°C	10
o	annealed at 300°C	7

[Ref. 7151]

CADMIUM OXIDE

REFRACTIVE INDEX (n)



Refractive index as a function of wavelength for cathode sputtered cadmium oxide films from 0.2 to 1 micron thick, at 300°K.

Graph	Carrier Concentration n (10^{20} cm^{-3})
a	12.1
b	1.32

[Ref. 5183]

Value (n)	Sample	Test Method	Ref.
2.49	powder sample	oil immersion λ_{Li}=.6708 micron	Ksanda*

*KSANDA, C.J. Comparison Standards for the Powder Spectrum Method - Nickel Oxide and Cadmium Oxide. AMERICAN J. OF SCI., v. 22, 1931. p. 131-138.

CADMIUM OXIDE

RICHARDSON'S CONSTANT (A)

Richardson's Constant, amp/cm^2 deg^2	Method	Ref.
1.65×10^{-6}	thermionic emission (sample specification not available)	6937

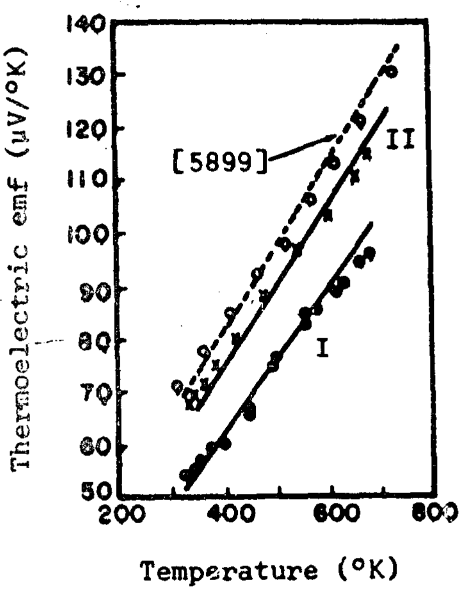
CADMIUM OXIDE

THERMAL CONDUCTIVITY (k)

Value (watts/cm deg)	Ref.
0.007	7359
0.0088	24169

CADMIUM OXIDE

THERMOELECTRIC PROPERTIES



Thermoelectric emf as a function of temperature for sintered, cadmium oxide powder heated 24 hours at 1000°K and prepared as strips.

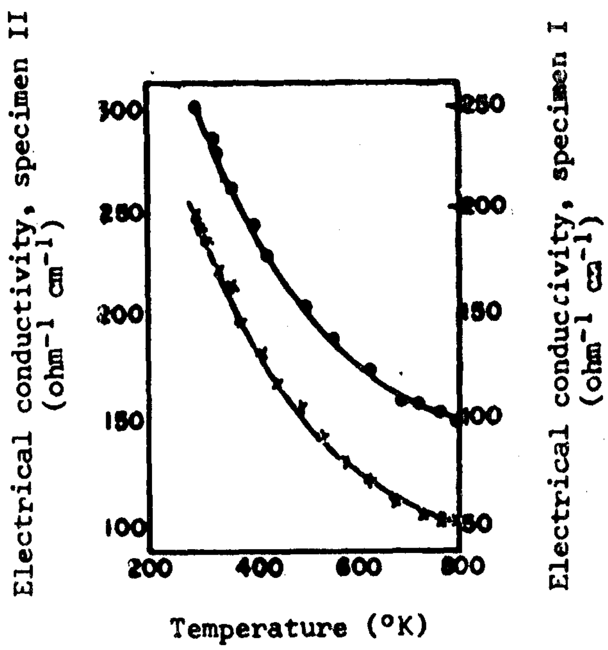
Symbol	Carrier Concentration n (10^{19} cm^{-3})
●	1.7
x	1.6

[Ref. 2189]

o polycrystalline material, either loose powder or pellets. [Ref. 5899]

Electrical conductivity as a function of temperature for the same cadmium oxide strips.

Curve	Carrier Concentration n (10^{19} cm^{-3})
●	1.7
x	1.6



[Ref. 2189]

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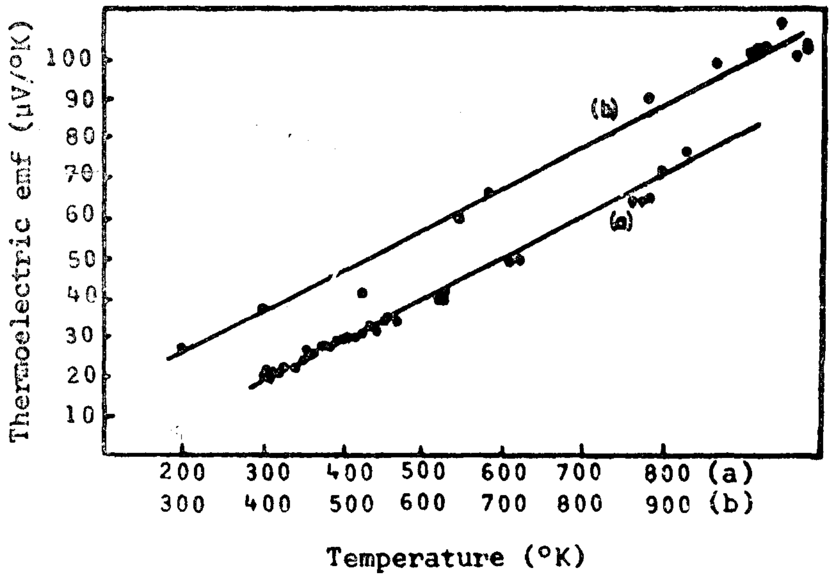


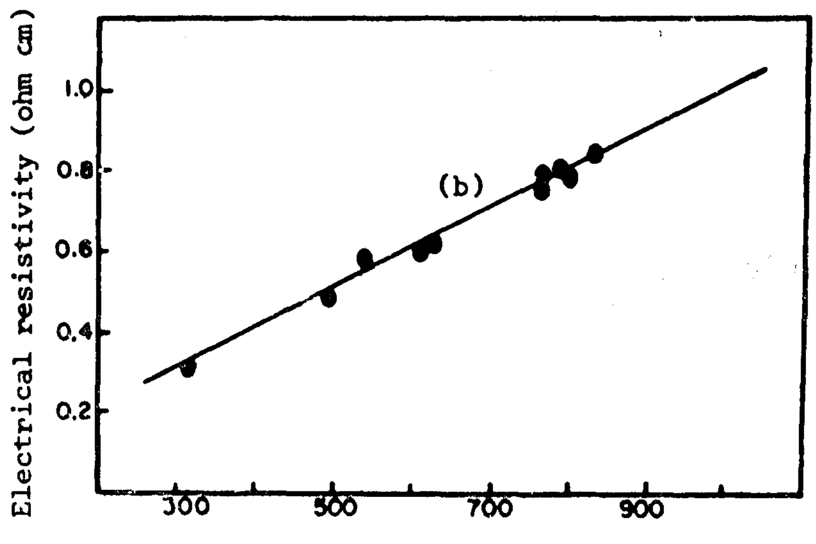
Thermoelectric emf as a function of temperature for sintered cadmium oxide pellets. Power curves are calculated for a free electron concentration of:

a) 2.26×10^{21} cm^{-3}

b) 1.58×10^{21} cm^{-3}

[Ref. 20243]

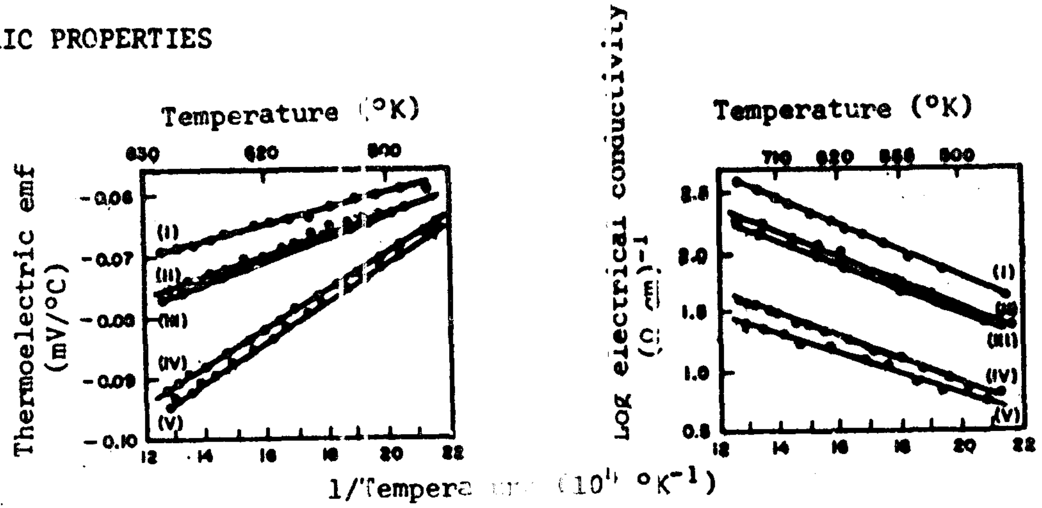
Resistivity as a function of temperature for pellet (b).



[Ref. 20243]

CADMIUM OXIDE

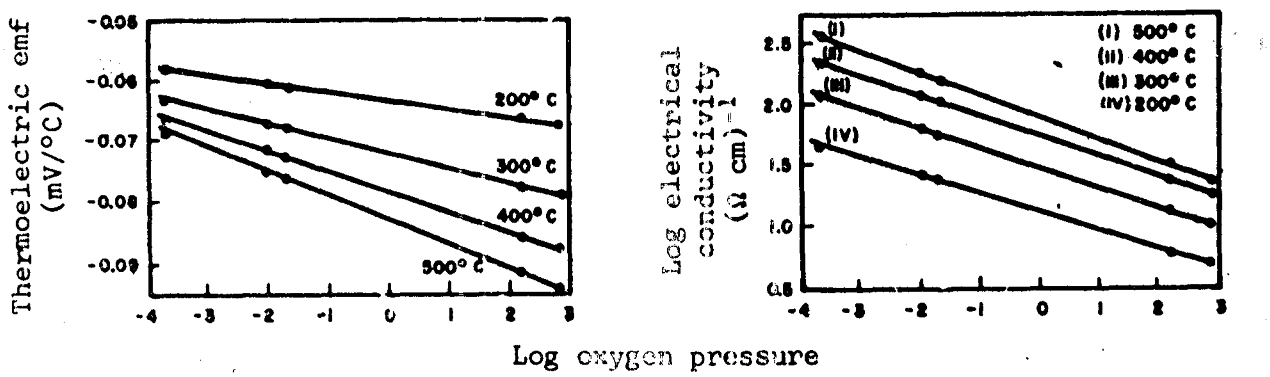
THERMOELECTRIC PROPERTIES



Thermoelectric emf and log electrical conductivity as a function of reciprocal temperature for pressed powder cadmium oxide samples prepared in oxygen or air at several pressures.

I. 0.01 mm air
II. 0.01 mm oxygen
III. 0.1 mm air
IV. 7[illegible]2 mm air
V. 7[illegible]7 mm oxygen

[Ref. 11654]



Thermoelectric emf and log electrical conductivity as a function of the log oxygen pressure at four temperatures for pressed powder cadmium oxide.

[Ref. 11654]

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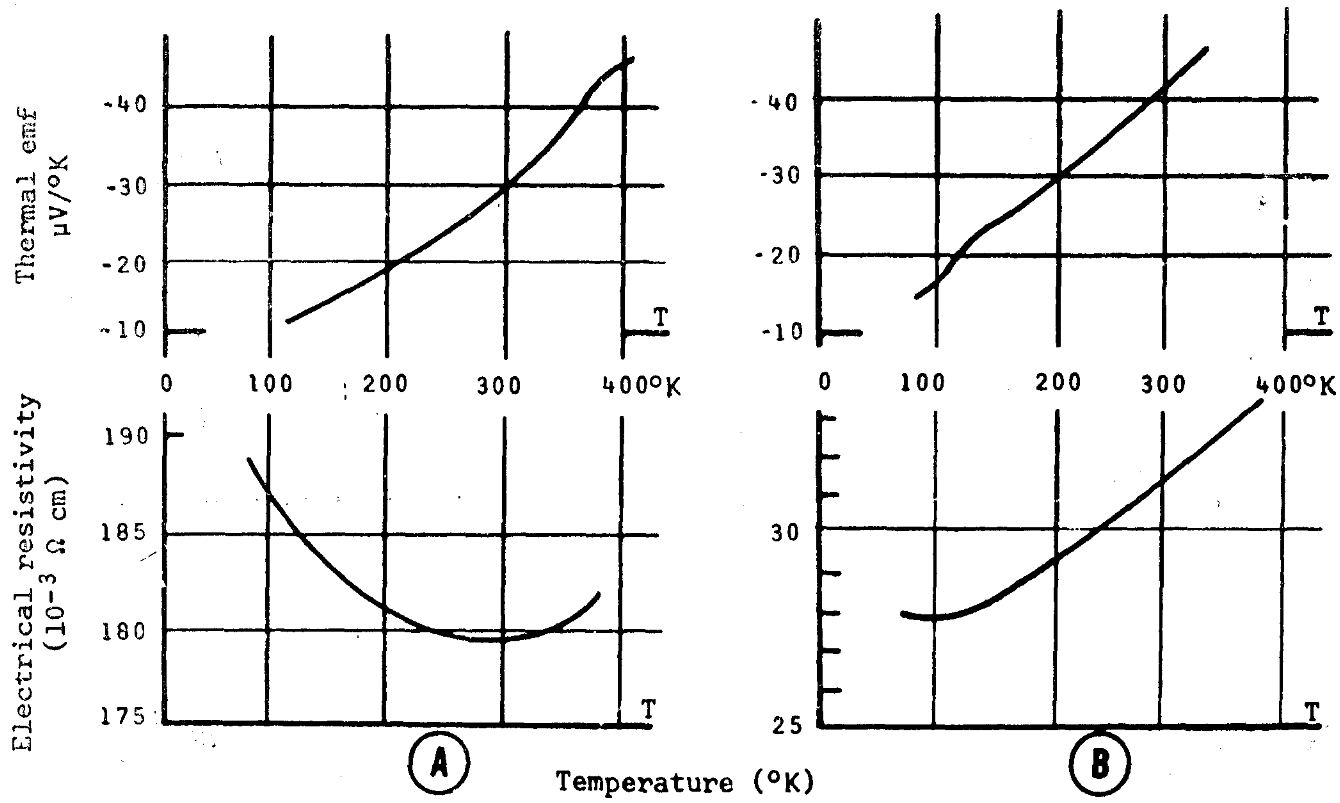


Thermoelectric emf and electrical resistivity as a function of temperature for compressed cadmium oxide powder.

A $n_n = 5 \times 10^{19}$ cm^{-3} at 293°K, ∿ 0.35% excess divalent cadmium ions.

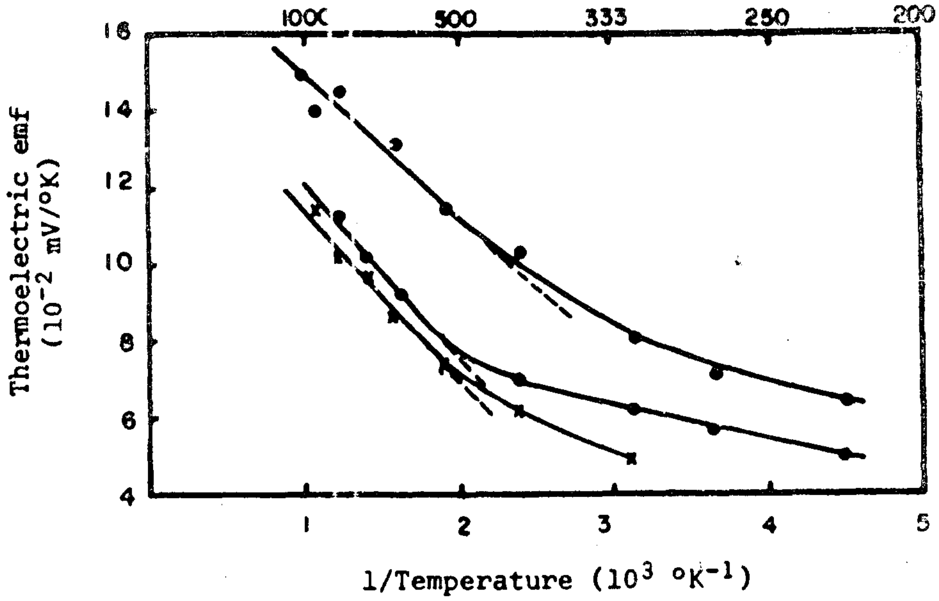
B Annealed in air at 320°C for 72 hours, ∿ 0.5% excess divalent cadmium ions.

[Ref. 12730]

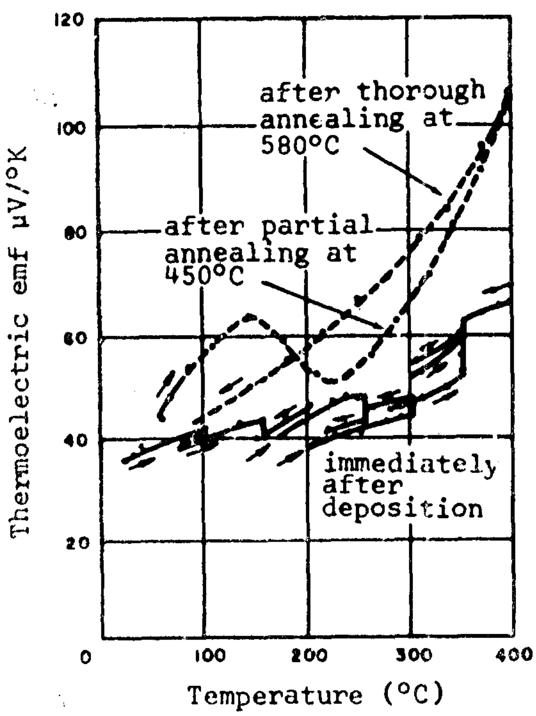
CADMIUM OXIDE

THERMOELECTRIC PROPERTIES

Thermoelectric emf as a function of temperature for dense cadmium oxide pellets, prepared by calcining cadmium carbonate pellets. The three curves represent data taken on three separate samples.



[Ref. 5899]

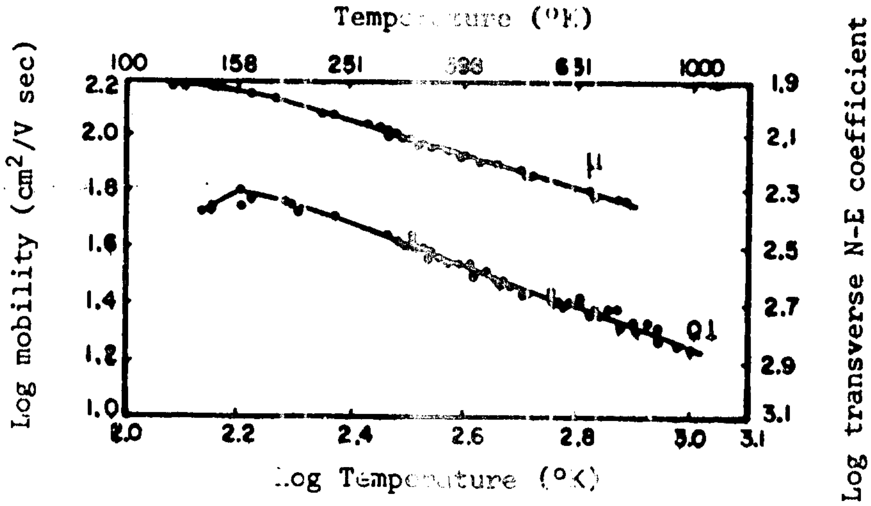


Thermoelectric emf as a function of temperature for cathode sputtered cadmium oxide films, thoroughly annealed at 580°C, $n_n = 5 \times 10^{19}$ to 5×10^{20} cm^{-3}. (Annealing smooths the curve.)

[Ref. 22103]

CADMIUM OXIDE

THERMOMAGNETIC PROPERTIES



Transverse Nernst-Ettingshausen coefficient of several crystalline cadmium oxide samples as a function of log temperature; $n = 10^{18}$ to 10^{19} cm^{-3}. H = 7400 Oe.

[Ref. 8798]

CADMIUM OXIDE

WORK FUNCTION (ϕ)

Work Function, eV	Measurement	Ref.
2.43	Thermionic emission	6837

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Data Sheets

5. AUTHOR(S) *(Last name, first name, initial)*

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13. ABSTRACT

These data sheets present a compilation of a wide range of electronic properties for cadmium oxide. Electrical properties include conductivity, dielectric constant, Hall coefficient, and mobility. Emission data have been broken down into the varied electron and photon emissions which result from application of electromagnetic energy over a wide spectrum. Energy data include energy bands, energy gap, and energy levels, as well as effective mass tables, and work function. The optical properties include absorption, reflection, and refractive index. Magnetic data are presented, as well as several other physical phenomena, such as Debye temperature. Thermoelectric and thermomagnetic properties are shown. Each property is compiled over the widest possible range of parameters including bulk and film form, from references obtained in a thorough literature search.

A summary of crystal structure and phase transitions has been included.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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